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SIMULATION OF FACTORY LEAD TIME IMPACT OF MODULARITY IN PROJECT BUSINESS

Master's thesis

Examiner: prof. Jussi Heikkilä

ABSTRACT

SAMULI HEIKKILÄ: Simulation of factory lead time impact of modularity in project business
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Slowly, project and product businesses have converged closer to each other. Products are getting ever more customizable while project businesses aim to find commonality in their customer needs to fulfil them with more standardized offering. Modularity has been one concept that has enabled this converging, by offering efficient way to customize products, and on the other hand offering way to fulfil complex customer needs with predefined system blocks, modules. Literature suggests, that modularity can help project business achieve lead time reduction in its operations, but literature quantifying the lead time impact is scarce, or even non-existent. This study creates preliminary understanding of factory phase lead time impact of modularity in project business and illuminates the critical factors affecting the lead time impact.

Study is conducted by first determining the factory phase lead time and delivery process for current, non-modular, system. Lead time is determined from combination of archival ERP data for past system deliveries and delivery process knowledge gathered from interviews. After this, simulation model for upcoming modular system was created on the basis of insights gained from literature, case company's current delivery process and company's vision of upcoming modular product structure. Using this simulation model, the research objective of critical factors and their impact to factory phase lead time could be fulfilled.

Simulation results indicate significant lead time reduction for chosen system scope. Total system factory phase lead time was reduced from 20 weeks to 10,3 – 13,3 weeks, depending on chosen simulation parameters. Lead time reduction potential is mostly determined during the modular product structure development phase. The clever design decisions that find the right balance between commonality and customization of the system enable process resequencing, process standardization, component standardization and multiple points of differentiation which in turn make it possible to postpone the order penetration point and reduce the system's factory phase lead time

TIIVISTELMÄ

SAMULI HEIKKILÄ: Simulaatio modulaarisuuden vaikutuksesta läpimenoaikaan projektiliiketoiminnassa
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Tuote- ja projektiliiketoiminta ovat hiljalleen ajautuneet lähemmäs toisiaan. Tuotteisiin tarjotaan jatkuvasti enemmän kustomointimahdollisuuksia, ja toisaalta projektiliiketoiminnassa pyritään löytämään yhteisiä tekijöitä asiakkaiden tarpeissa, jotta ne voitaisiin täyttää entistä tehokkaammin vakioidummilla ratkaisuilla. Modulaarisuus on toiminut yhtenä näiden liiketoimintojen lähentymisen mahdollistavana tekijänä, tarjoamalla tuoteliiketoiminnalle tehokkaan tavan kustomoida tarjoamaansa, ja toisaalta mahdollistanut monimutkaisten asiakastarpeiden täyttämisen projektiliiketoiminnassa ennalta määrätyillä rakennuspalikoilla, moduuleilla. Kirjallisuudessa on tunnistettu modulaarisuuden mahdollisuudet lyhentää läpimenoaikaa projektiliiketoiminnassa, mutta tutkimukset, joissa tarjotaan konkreettisia tuloksia, ovat harvinaisia tai niitä ei ole ollenkaan. Tämä tutkimus luo alustavaa ymmärrystä siitä, miten modulaarisuus voi vaikuttaa tehdasvaiheen läpimenoaikaan projektiliiketoiminnassa, ja siitä mitkä ovat kriittisiä tekijöitä läpimenoajan lyhenemisessä.

Ensin tutkimuksessa määritettiin nykyisen järjestelmän tehdasvaiheen läpimenoaika tutkimalla ERP-järjestelmästä saatavaa dataa menneistä projekteista, ja yhdistämällä sitä haastatteluissa toimitusprosessista kerätyn tiedon kanssa. Tämän jälkeen kirjallisuuskatsauksen, yrityksen nykyisen toimitusprosessin ja yrityksen modulaarisen tuoterakenteen vision pohjalta luotiin simulaatiomalli, jota käytettiin arvioitaessa uuden modulaarisen järjestelmän läpimenoaikaa ja tunnistamaan siihen liittyviä kriittisiä tekijöitä.

Simulaatiomallin mukaan modulaarisuuden vaikutus läpimenoaikaan, valitulle järjestelmälle on merkittävä. Tehdasvaiheen läpimenoaika lyheni 20 viikosta 10,3 – 13,3 viikkoon, riippuen valituista simulaatioparametreista. Potentiaali läpimenoajan lyhenemiselle määritellään pitkälti modulaarista tuoterakennetta suunniteltaessa. Kekseliäät suunnitteluratkaisut, joiden avulla löydetään sopiva tasapaino rakenteen samankaltaisuuden ja yksilöitävyyden välillä mahdollistavat prosessien uudelleenjärjestämisen, prosessien ja komponenttien standardoinnin ja usean differentoitumispisteen prosessin aikana. Tämän seurauksena asiakastilauksen läpäisypistettä toimitusprosessissa voidaan viivästyttää ja näin lyhentää järjestelmän tehdasvaiheen läpimenoaikaa.

PREFACE

I started working with this thesis in the end of 2016 and after almost exactly two years, it is finally done. Journey that started with much excitement soon branched to doing different analyses for the company, because doing analyses was fun. Not because I would use them for my thesis, but because it was fun. Suddenly I was in a situation where I had used whole 7 months reserved for making this thesis, and thesis was not even close to being ready. What I had was numerous amount of analyses, good understanding of the process and a thesis that was stuck.

After the official thesis worker employment, I was hired as a business controller to the same company. My plan was to finish the rest of the courses left quickly and then just finish the thesis so I could focus on my new employment. Completing the courses while working was a cakewalk but allocating time for thesis proved problematic as the burden of work left in the thesis felt overwhelming and I did not know where to start.

Eventually by some combination of peer-pressure and friendly reminders from professor, I decided to scrap large part of the work I had done earlier and redo this thesis as I saw fit. I came up with more or less the current idea of the thesis and I was happy with it. After this, working with the thesis was pleasant, and I even often got carried away while polishing the ins and outs of the simulation model. Slowly, when work and personal life allowed, I wrote and iterated the thesis, and now it is finally finished.

The journey from start to finish has included vast amount of learning from myself, time management and taking responsibility of things I am in charge of. The journey might have been overly long, but on the other hand I have enjoyed most of it and gained a lot of understanding that I couldn't have gained without it. I regret nothing.

Biggest thanks for supporting me during the process goes to my personal thesis dog Tove, who slept on my lap for possibly hundreds of hours while I wrote. Thanks to Eeva, who has been the source of much happiness during these few years. Thanks to my whole family for always supporting me and telling me I can go anywhere I want in life. And special thanks to professor Jussi Heikkilä for having the patience and understanding with me and this thesis.

Tampere, 25.10.2018

Samuli Heikkilä

CONTENTS

ABBREVATIONS AND SYMBOLS

ATO	Assemble-to-order
ATO_{ED}	Adjust-to-order, engineering dimension
ATO_{PD}	Assemble-to-order, production dimension
BTO	Build-to-order
CODP	Customer order decoupling point
DMC	Double mast crane, name of Fastems system component
ERP	Enterprise resource planning software
ETO	Engineer-to-order
ETO_{ED}	Engineer-to-order, engineering dimension
ETS_{ED}	Engineer-to-stock, engineering dimension
FAT	Factory acceptance test
LSM	Loading station moving, name of Fastems system component
MDR	Medium duty rotating, product class name for Fastems multilevel system
MLS	Multilevel system, Fastems product name
MTO	Make-to-order
MTO_{PD}	Make-to-order, production dimension
MTS	Make to stock
MTS_{PD}	Make-to-stock, production dimension
NPD	New product development
OPP	Order penetration point
SQL	Structured query language, programming language used in databases
STS	Ship-to-stock
VBA	Visual basic programming language

1. INTRODUCTION

Project business, by definition, is about delivering something unique (Gosling, Jonathan, Naim, 2009). Uniqueness is not a value in itself, but sometimes economic actors find themselves in a situation where their need is so specific, that no productized offering that fulfils the need, is available. This is the need that project business aims to fulfil, the need for customization.

The simplified difference between product and project business has been, that for products, all the incurring costs of developing and delivering the product are divided to thousands, millions, or however many units is produced, as in project business all the costs are covered by single produced unit. In reality, many project businesses of today aim to shift towards product business on search for competitive advantage, for example reusing work done in the previous projects, adapting manufacturing technologies used in product business and creating mass customized offerings. On the other hand, many product businesses are shifting towards project business as customers demand ever more personalized products – The clear division between project and product business is slowly fading away.

For the subject company of this study, Fastems Oy, above depicted setting is very relevant at the moment. Fastems Oy offers highly customized factory automation solutions for manufacturing companies in multiple industries. In the past, being a technology leader and possibly the only one able to fulfil the potential customer's need, was enough competitive advantage to survive and even strive in the markets. Now, the competitive situation has changed. There are multiple competitive alternatives in the markets to Fastems offering, and this has forced Fastems to rethink the way they deliver their solutions. For some time, Fastems has launched different development initiatives ranging from company culture development to offering and delivery process renewal. This study is a part of a development program aiming to create a new modular offering and delivery capabilities for that offering.

The role of this study in development of modular offering and delivery capabilities at Fastems, is to create understanding of how modularity will affect the lead time of the system, and on the other hand, identify what is critical in the development of modular offering and new delivery capabilities to reduce the lead time of the system. From theoretical point of view, this study contributes to still limited research area in the crossroads of project type business, modularization and order penetration point postponement, which can be interesting area in the future considering the direction the competition in the project business is heading.

1.1 Fastems Oy

"Fastems is the leading independent manufacturer of factory automation systems". Employing approximately 400 people worldwide, Fastems aims to improve its customers competitiveness with intelligent automation and software solutions. Main customer segments reside in aircraft and aerospace industries, engineering and machine building industries, construction and mining machinery manufacturer industries and part manufacturing and assembly industries. (Fastems, 2018).

Main geographical market areas by sales volume are focused to central Europe and USA. Fastems has over 4000 installed systems worldwide, with customers ranging from small machining job-shops to aerospace manufacturers. Fastems product offering ranges currently from small product-like Flexible Pallet Containers, that can be delivered to customer from stock, to large tailored manufacturing systems that can automate complete portions of customer's manufacturing process. Fastems Lifecycle Services complete the offering with different support possibilities for delivered systems (Fastems, 2018).

1.2 Research objective

This research will be part of the Fastems' modularization project, including the creation of modular offering and creation of modular delivery capabilities at Fastems. So far research plan has introduced what is the current situation at Fastems and what is the context that this research will be executed in.

Research objective of this study was to **evaluate the impact modular product structure will have on project delivery lead time and identify the critical factors that enable the lead time impact.**

To fulfill the research objective defined above, problem was divided to the following phases:

1. Define the present state of lead time
2. Estimate the future state of lead time
3. Analyze the lead time difference between present and future states
4. Identify critical factors enabling the lead time difference between present and future state

1.3 Research limits

Simplified project delivery process for current systems is illustrated in figure 1, as specified by this study's company steering group. Delivery process starts after sales process is complete and customer has placed an official order, marked as order penetarion point in the figure. First phase of the delivery process is design according to customer specifications.

Purchasing phase starts after design is ready and all the information for purchases is available. During the purchasing phase, all the materials that are not stocked are ordered and delivered to specified locations.

Assembly phase starts after the needed items have been delivered to factory. Assembly phase's duration is dependent on the project size and can vary from few weeks to several months. After assembly phase is complete, all the items and subsystems are packed and sent to customer site.

Installation and commissioning at customer site start when materials have arrived to site. After installation is complete, commissioning team starts to ramp-up and test the system to meet the customer demands. Delivery process ends after commissioning is finished and customer has accepted the delivery as complete.

This research scope will be limited to design, purchasing and assembly phases of the project delivery process, later referred to as "factory phase" of the delivery process. This limitation is illustrated in figure 1 with yellow box.

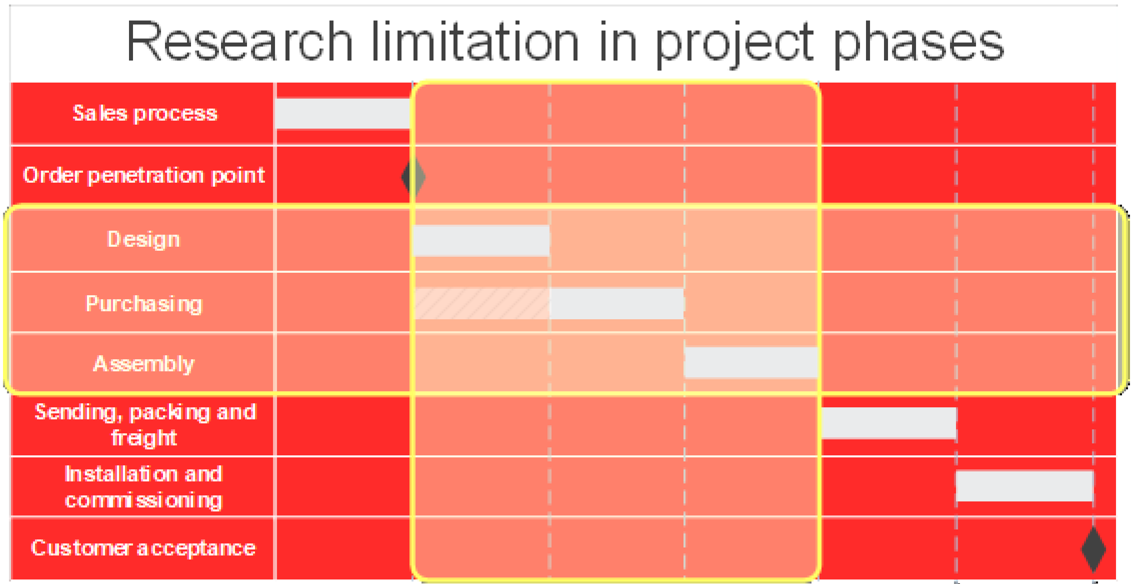

Figure 1: *Research limitation in project delivery process phases*

Scope of this research is also limited in supply chain to concern only case company and its first-tier suppliers that deliver items straight to the case company. This limitation is chosen to keep the focus of this study in internal factor. First tier suppliers are included in this study superficially, as purchasing process lead time is direct result of their delivery capability. Illustration of this limitation is shown in figure 2 below. In figure 2, scope of this thesis is framed with gray box.

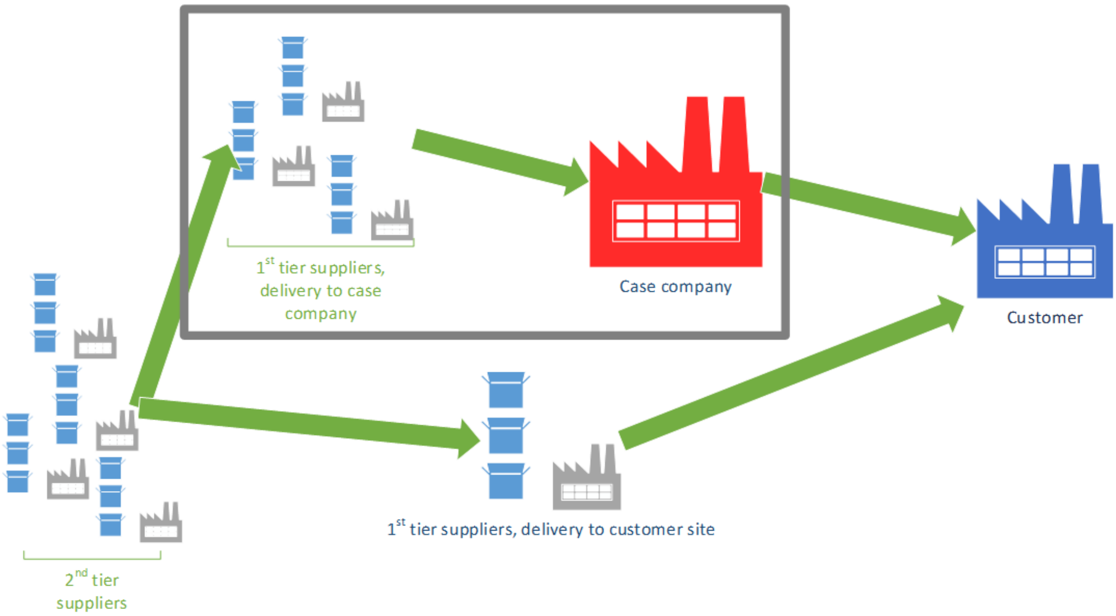

***Figure 2:** Research limitation in supply chain*

Operating in project business, Fastems' offering covers unlimited amount of possible system configurations to fulfill the customer need. For the needs of this study, the company steering group has defined an archetype of entry-level basic system configuration as follows:

- Aisle,
- Double Mast Crane,
- Loading Station Moving and
- Material Station.

This system configuration is used as it fulfills the functionality of basic system and can satisfy customer needs in notable part of sales cases. Storage is normally a part of every system configuration, but as the storage is delivered from supplier directly to the customer site, it is outside the scope of this study.

The **functionality** of above specified system scope will be used for defining the present state of lead time, and for estimating the future state of lead time with modular system. Limitation is done on the basis of functionality, as in the modular system, corresponding functionality might be reached with completely different system configuration.

1.4 Research methodology

This research is based on traditionally less used research methodology in the field of operations management (Holmström et al., 2009) – the design science methodology. Traditionally operations management research operates in the end of the theory creation chain as explanatory research form, explaining phenomena and testing theories and hypotheses created by practitioners. Researchers do not create novel solutions to problems faced by real life practitioners, but instead focus on explaining why solutions, that are already used by practitioners, work. Explaining how artifacts work is essential for building deep understanding of the subject matter, but it rarely adds value for practitioner facing new and poorly specified problems. (Holmström et al., 2009)

In the design science methodology, researcher takes part in creation of the solution and thus steps to the arena that has traditionally been left for practitioners to rule (Holmström et al., 2009). Holmström et. al. (2010) summarize use of design science methodology in research to three parts; Explore for fitting interventions and solution proposals and find promising context or problem definition; Abduct ideas from other areas to create specific solution proposals and reiterate preliminary problem definition and solution proposal if needed; Explain chosen solution proposal from the point of means-ends analysis by studying the intervention mechanisms of the proposed solution.

The research question in this study is loosely defined, as the primary objective of this study was to evaluate the impact of modularization to case company's factory lead time, and to identify critical factors affecting the lead time impact of modularization. To clarify, company is still operating with non-modular product structure and beginning its journey towards modularity, so no actual data about the modular system lead time is available. In this kind of setting, choosing the design science as research methodology is justified, as it enables working with ill-defined research questions systematically and exploring, abducting and explaining solution proposals and mechanisms behind it for practitioner's problem (Holmström et al., 2009, Holmström et al., 2010).

Regarding the methodological choices, this study fits in the philosophy of pragmatism; it aims to find the best solution proposal and explain the intervention mechanisms so that practitioner benefits from the results without strict philosophical restrictions. Ontology of this study is objectvism – we do not want to attach meaning to subjective experiences of social actors, but to study the objective dynamics of lead time.

In this exploratory study, primary data from interviews and secondary data from company's transactional system are critical sources of information. To refine objective knowledge from the interviews, we need to adopt the position of critical realist – we understand that what interviewees tell us is their interpretation of their sensory perception of reality, and we need to consider does that interpretation always reflect the reality. With the transactional system data, we can adopt the positivistic view. We assume the data is objective and we can find rules or generalizations from the data. By using the insights gained from interviews we can more efficiently analyze the secondary data, as both primary and secondary data concern the same phenomena.

Researcher understands that axiology wise the research is affected by his own values and earlier work experience in the case company. Working history with the case company and acquired knowledge can highlight the subjective experience of the researcher in the case company, but on the other hand it can help to create deeper understanding of studied delivery process.

Research paradigm positions itself to “Radical structuralist” class in a model first created by Burrell and Morgan (1982) and later developed by Saunders et al. (Saunders et al., 2000, p. 120). This is because research aims to examine the matter from objectivistic point of view and means impact the way how the company in question will organize its delivery process in the future with modular product structure

Research approach in this case is abductive. Data is first gathered about the research subject and analyzed, after which theory around the subject matter is researched and combined with the process knowledge gained during the earlier data gathering to form the assumptions and the simulation model of this study.

Time horizon of this study is cross-sectional. Longitudal time horizon would allow us to compare the simulation results to actual lead time impact of modularity and contemplate the causes behind the difference of simulated and actual lead time, but this is not possible due to time restrictions of this research.

1.5 Research process

First part of this study was the literature review. During the literature review, theoretical understanding of key concepts concerning this study was created. After the literature review, secondary data was gathered from company’s Enterprise resource planning software, ERP. The secondary data from ERP system included two datasets, one for analysing design and assembly lead times and one for analysing purchasing lead times. Primary data was gathered by conducting semi-structured interviews for experts of different areas of delivery process factory phase. Conducted interviews had theme areas which needed to be addressed in each interview, but the interview style was exploratory, as the aim of the interviews was to generate understanding and widen the perspective of the researcher regarding the subject matter. Primary and secondary data gathered for this study is summarized in table 1 below. Gathered data is grouped according to knowledge goal it is used to accomplish.

Table 1: *Gathered data for study*

Goal / Data source
Creating understanding of what is known and what is the vision of modular structure
Company documentation: MLS module map
Janne Aalto, interview, Technical product manager, Electric, 13.12.2016
Elmeri Tanskanen, interview, Technical product manager, Mechanical, 9.12.2016
Creating understanding of the underlying processes: design
Teemu Jaakkola, interview, Head of mechanical and electrical design department, 22.12.2016
Pertti Lukkari, interview, Head of software development department, 12.12.2016
ERP system's reported design hours (mechanical, electrical and software design)
Creating understanding of the underlying processes: purchasing
Jenny Jyrinki, interview, Purchasing team leader, 21.12.2016
ERP system's history data for purchase order lots
Creating understanding of the underlying processes: assembly and testing
Operations planning interview: Kari Molarius and Hannu Leinonen, 20.12.2016
Work planning interview: Maiju Lahti and Sten Lundberg, 15.12.2016
ERP system's reported assembly and testing hours

Methodology for current, non-modular, system lead time estimation was created iteratively by combining the knowledge gained from interviews with the insights gained while exploring the ERP's secondary data. Process was a combination triangulation to check that lead time estimation methodology aligns with interview and ERP data, and iteration as the methodology needed multiple iteration rounds before meaningful results could be reached. The final non-modular lead time estimation methodology is explained in the chapter 3 for each process phase with the non-modular lead time estimation results.

After defining the current situation in chapter 3, we started to build a methodology for simulating the lead time impact of modularity to system under investigation. Basis of the simulation methodology was on the already known facts, or strong assumptions, about the delivery process of the future modular system and the company vision of the modularity in the system, uncovered during the interviews. The known facts and vision were then combined with ideas and concepts from the literature review to create a set of assumptions about the future delivery process of modular system. According to these assumptions, detailed delivery process for simulation was conceived. In addition to being able to allocate lead time impact of modularity to separate factors in this simulation model, a sensitivity analysis was integrated in the simulation to create preliminary understanding of the system's dynamics regarding the lead time impact. Sensitivity analysis was integrated by conducting the simulation in two scenarios: a base scenario where assumptions were adjusted to match the expectation of future process with the company's steering group, and a risk scenario, where assumptions were changed in chosen parts to reflect suboptimal implementation of modular system's delivery process.

In the end, the simulation model for modular system lead time materialized as a set of calculation rules, which were then used to calculate the modular system lead time in base and risk scenarios. The difference between non-modular system lead time estimation and simulation of modular system lead time was then analysed and allocated to main impact factors: impact to purchasing lead time, impact to design lead time, impact through parallel assembly, impact through forecast driven assembly and impact of disconnecting process dependencies. In the end of the study, these factors were assessed by their lead time impact and sensitivity. Also, the connections between impact factors and assumptions were clarified to highlight the most critical matters when trying to reach the simulated lead time reduction during the implementation of modular product structure.

2. LITERATURE REVIEW AND RESEARCH POSITIONING

2.1 Time based competition

In 1988 George Stalk, JR., the vice president of Boston Consulting Group at the time, declared “Today, time is the cutting edge (*of competition*). The ways leading companies manage time – in production, in new product development and introduction, in sales and distribution – represent the most powerful new source of competitive advantage”. Time has also been praised as the new competitive edge by other authors like Musselwhite (1990), Stonich (1990) and Kumar (1995). Strategic value of time is born from

- faster response time allows price premium,
- faster delivery of tailored offering increases brand loyalty and market share and
- faster pace of activities improve operational performance and lead to better profitability (Kumar, Motwani, 1995).

Evolution from traditional cost- to time-based competition is most clearly seen in Japanese manufacturing companies changing from one competitive advantage to another when adjusting to dynamic market and competition situations. First, after the second world war Japanese companies used extremely low labor costs, that were caused by devaluation of yen, to compete in the global markets. After competitive advantage of low wages was starting to evaporate, Japanese companies shifted to using economies of scale as their competitive advantage. Japanese started building large high-tech factories to drive down the manufacturing costs and to stay ahead of the competition. (Stalk, 1988)

Next step in search for more competitive advantage was to move on to focused factories. This strategy was based on the higher productivity of factory that had less manufacturing variety, thus called the focused factory strategy. Focused factories manufactured products that had high volume and manufacturing variety was very limited. This way Japanese companies were able to build small establishments close to customers and still be able to achieve lower costs than their colossal western competitors. (Stalk, 1988) The impact of increased productivity and consequent toughening competition coming from focused factory strategy was also felt in the US. In article “The focused factory”, Skinner lays down the facts representing that era: US labor was the most expensive in the world, its productivity had been increasing slower than the competitions and this had caused drop in imports which in turn had led to masses of industrial workers been left unemployed (Skinner, 1974).

From focused factories, Japanese industry moved to flexible factories. Flexible factories aim to decrease the effect of increased unit costs when widening the product variety of factory, thus enabling Japanese companies to maintain their cost leadership while they expand product variety. One of the pioneers of flexible factory was Toyota Motor company, which deployed its core philosophies, known today as lean principles, and famous Toyota production system to its suppliers, making the whole supply chain more competitive in terms of flexibility and productivity. (Stalk, 1988) Flexible factories enabled companies to expand their selection and compete with variety while keeping costs down (Stalk, 1988), even though flexible factory strategy has its opponents too. For example, Levitt (1984) in article “The globalization of markets” argues that even though in theory flexible factories offering superior variety with the costs of focused factory appear compelling, in reality achieving economies of scale like in mass production is almost impossible.

In the boom of flexible factories, Yamaha tried to challenge the leading market position of Honda by publicly claiming the title of biggest motorcycle manufacturer in the world. Honda answered to this by flooding the market with new motorcycles. To be exact Honda made 113 new models to its product line during 18 months. Yamaha tried to counteract but failed by delivering only 37 changes during the same 18 months period. Yamaha’s products were soon outdated compared to Honda’s quickly revolving product line and Yamaha had to eventually submit and publicly apologize for starting the direct attack against Honda. Honda had adapted the time-based strategy for its operations and was thus able to rapidly introduce model after model new motorcycles for the market and eventually beat Yamaha in the war that Yamaha had started. (Stalk, 1988)

Conventionally company aims to reduce its costs by maximizing resource utilization rates (Modig, Åhlström, 2013). To achieve this, company needs to buffer orders to create large lot sizes and plan the production so that utilization rates are high. Even though utilization rates can be maximized using this strategy, individual order’s lead time, the time it spends in the system between order and delivery, gets very high and at the same time the value-added time to product gets usually as low as 0,05-2,5% of the total time spent on the factory. (Stalk, 1988) Focusing on resource utilization rates can drastically increase lead times, which in turn often create so called secondary needs. These secondary needs risen from the long lead time cause customer dissatisfaction if not addressed, and often changes to original plan need to be made. (Modig, Åhlström, 2013) Any deviations in a rigid system designed to maximize resource utilization can be tricky to handle and for example rush orders need huge efforts to reorganize the production schedule. Flexible factories brake the vicious cycle of so called “planning loop” and its negative effects by focusing on shortening the cycle times in all of the company’s functions. (Stalk, 1988)

Companies that adopt the time-based competitive strategy can realize notable improvements in their manufacturing, sales and distribution and innovation operations. Flexible factories focusing on manufacturing high variety of products with short lead time in small batches often achieve multiple times faster response times and at the same time, achieve significantly lower costs compared to their traditional factory counterparts. (Stalk 1988) Time compression has been noticed to be effective way to improve efficiency and for example, in construction industry reducing lead time by 40% decreased costs and work done by 25% (Towill, 2003).

Koufteros et al. (1998) identifies seven key practices found from literature, that enable shortening factory's lead time and thus enable time-based manufacturing. These practices are

- factory employee involvement in problem solving,
- re-engineering set-ups,
- cellular manufacturing,
- quality improvement,
- preventive maintenance,
- trustworthy suppliers and
- pull production. (Koufteros et al., 1998)

Factory employee involvement is in integral role of developing time-based manufacturing capabilities. Shop floor employees are the ones continuously operating in the environment where many of the other time-based manufacturing practices are implemented and thus they have extensive operational understanding of many problems that need to be solved. (Koufteros et al., 1998)

Re-engineering set-ups to reduce set-up times increases flexibility by minimizing the downtime caused from product changes (Dillon, Shingo, 1985). This in turn decreases the minimum feasible patch size, reduces inventories and further increases flexibility (Ohno, 1988).

Grouping manufacturing processing capabilities together so that group, or so-called manufacturing cell, has the ability to manufacture certain group of products from start to finish is called cellular manufacturing (Pullen, 1976). As manufacturing cells are self-contained, materials are not moved between manufacturing areas and thus material handling is minimized, work-in-progress is decreased, and lead time is shortened. Also increased quality and flexibility is achieved when using manufacturing cells. (Hyer, Wemmerlov, 1984)

Quality improvement plays a key role in the time-based manufacturing strategy. Quality lapses in production cause deviations to process that send long reaching ripples to manufacturing process. Items might need to be remanufactured or repaired, which causes variations to production plan and might cause work-in-progress to build up while recovering from the quality issue. Poor quality requires more inspection work which in turn lengthens the lead time of manufacturing. (Schmenner, 1992)

Preventive maintenance reduces the risk of manufacturing downtime as equipment are in good shape. Possible downtimes cause companies to increase inventories which in turn increases wait-times and lead time. It is wise to participate employees on preventive maintenance planning and execution, as it has been identified as a part of effective preventive maintenance plan by many practitioners. (Koufteros et al., 1998)

Reliable suppliers also contribute to time-based manufacturing. Delivery delays cause company to increase its inventories, and cause problems when materials shortages appear (Im, Lee, 1989).

Pull production reduces the work-in-progress and wait times and decreases the throughput time of manufacturing. Achieving pull production is natural consequence of implementing above mentioned practices that help companies to achieve shorter lead time and time-based manufacturing strategy. (Koufteros et al., 1998)

The seven practices explained above have been identified as enablers of shortening lead time and engaging in time-based manufacturing strategy. For project delivery supply chains, purchasing, competitive bidding and design have been identified as usual problem areas concerning lead time reduction (Elfving et al., 2005, Gosling, Jon et al., 2007).

Like manufacturing, sales and distribution channel is also suspect to increased performance when engaging in time-based strategy. Reducing lead time cuts costs. Good example from this was Toyota's sales and distribution channel which accounted for more costs than the actual car manufacturing in the whole car sales process. After implementing processes to cut lead time in sales and distribution, lead time was cut from four to six weeks to eight days and at the same time costs were decreased (Stalk, 1988).

Company's innovation ability is also reinforced by time-based strategy as happened with Honda Yamaha variety wars. Being able to develop and introduce new product innovations iteratively with short cycle time lead to continuous development and eventually lead to technological superiority compared to traditional companies incubating their major product development projects for years before release (Stalk, 1988)

2.2 Mass customization

Since the identification of economies of scale in manufacturing, companies have danced around the tradeoff of manufacturing costs versus product variety. As explained earlier in the evolution of time-based competition in Japan, companies first adapted the perks of economies of scale with minimum variety, and after that started to develop ways to increase manufacturing variety without sacrificing the productivity.

As time has passed, companies have been able to develop more and more ways to manufacture products that are ever better fitted to individual, i.e. more varied, customer needs with the price of mass manufactured product. This endless cycle of competition in the markets has created a situation where companies have to be able to rapidly fulfill customer needs that can't be anticipated or forecasted, with almost the price off mass produced goods. On the other hand, companies that have manufactured one-of-a-kind and tailored products are facing toughening competition as competitors are adapting ways to produce project-like offerings by utilizing lessons learnt in high-volume industries. (Haug et al., 2009)

Mass customization is one of the concepts developed to help companies in their struggles explained above. Mass customization term was first introduced by Davis in his book "Future Perfect" in 1987. The aim of mass customization as explained by one author "*is to offer customers customized products (goods and services) at prices close to the ones of mass production*" (Haug et al., 2009). According to Davis (1989) this can be achieved by using new technologies that enable mass production of customized products. The definition of mass customization is very broad and in the context of this study we define mass customization as *the overarching concept that groups together all the concepts that aim to produce customized goods by exploiting tools of mass production*.

2.3 Modularity

According to Baldwin and Clark (2000) the only way for humans to solve complex problems is to break the problem to smaller pieces and then individually solve these smaller pieces. Modularity uses this concept to divide complex system to smaller independent subsystems. These subsystems can then be handled individually to reduce the amount of complexity needed to handle complete system.

Modularity can be described by two characteristics of modularity:

1. *"A module is a unit whose structural elements are powerfully connected among themselves and relatively weakly connected to elements in other units. Clearly there are degrees of connection, thus there are gradations of modularity."*
2. *"Abstraction, information hiding, and interface" (Baldwin, Carliss Young, Clark, 2000)*

First characteristic points out that module is structurally interconnected entity, and at the same time is module is externally decoupled from other modules of the system and together these modules form complete functional system. Degree of modulation characterizes how well the individual modules are decoupled from each other.

Baldwin and Clark (2000) synthesizes the rationale for second characteristic from different definitions of design literature as

> "*A complex system can be managed by dividing it up into smaller pieces and looking at each one separately. When the complexity of one of the elements crosses a*

> *certain threshold, that complexity can be isolated by defining a separate abstraction that has a simple interface. The abstraction hides the complexity of the element; the interface indicates how the element interacts with the larger system"*

Modular product can also be described as a system that can be assembled from independent modules that are engineered independently from other modules and together they form integrated functional product (Baldwin, Carliss Y., Clark, 1997). According to Yang (2004) modularity can be divided to two categories: modularity in design and modularity in production.

Modularity in design is the defined design rules, or architecture, about how product is divided to modules, what should be module's inputs and outputs and what kind of physical interfaces it has to other modules and standards regarding the testing of the module (Baldwin, Carliss Y., Clark, 1997). Heikkilä et al. (2002) synthetize this complete design rule set as

- *architecture,*
- *interfaces and*
- *integration protocols and testing standards*.

The meaning of these design rules is to create modules that are decoupled from each other and thus enable designing the modules individually without the knowledge of the whole system (Yang et al., 2004). Product structure in which design change made to one module does not affect any other module in the system can be called fully modular architecture in contrast to integral architecture, where system parts are highly coupled and change to one part requires changes to other parts (Ulrich, 1995).

Great example of modular product design is todays personal computer. Computer is divided to Lego-like parts. These parts have design rules and standards they must comply with, but the design of module itself is in the hands of any manufacturer that wants to manufacture these parts. Customer can buy motherboard from Asus, central processing unit from Intel, hard drive from Samsung and graphics processing unit from MSI and expect these system parts to work together flawlessly thanks to modularization and standardization.

Modularity in production is to manufacture the end product in pieces and combining the subassemblies in the end to form functional final product (Baldwin, Carliss Y., Clark, 1997). This simplifies the manufacturing process, as the manufacturing can be divided to independent cells which produce parts of the system according to engineering specifications (Baldwin, Carliss Young, Clark, 2000).

In a core of many successful companies are good products. In the center of sustainable development of successful products lie product platforms. (Meyer, Lehnerd, 1997) Useful definition for product platform in the context of this study is offered by Meyer and Lehnerd (1997):

> *"A product platform is a set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced."*

In 1990s Boeing started to develop consistent product platform for its aircraft to unify the numerous different architectures it had, and to tackle the long new product development cycle times. As a result, Boeing created the 777-platform. Major part of all 777 aircraft is standardized and the platform can be derived to different products with relative ease instead of designing whole aircraft from scratch. Due to shared product platform there is a great amount of commonality between planes which supports efficient operations. For example, Boeing aircraft doors had approximately 1400 parts, of which most where unique. In the 777, 95 % of the door components are common. (Meyer, Lehnerd, 1997)

Even though the 777 is highly standardized, the platform allows great deal of customization. Platform makes the customization very efficient as the customization perspective is integrated to the 777-platform. (Meyer, Lehnerd, 1997)

2.4 Order penetration point and supply chain process type

Order penetration point, OPP, according to Olhager (2003) is traditionally defined as "*the point in the manufacturing value chain for a product, where the product is linked to a specific customer order*". Sometimes authors use the name "customer order decoupling point", CODP, in the same meaning as order penetration point is used. Gosling (2009) in his literature review article compiles more precise definition for customer order decoupling point from the works of Christopher (2000), Hoekstra and Romme (1992), Mason-Jones et al. (2000), Naylor et al. (1999) and Olhager (2003) as:

> "*The customer order decoupling point (CODP) is a stock holding point that separates the part of the supply chain that responds directly to the customer from the part of the supply chain that uses forecast planning."*

Gosling elaborates the definition by stating that "*The decoupling point can act as a strategic buffer against the variability in demand and an efficient way of scheduling standardised parts whilst reacting to uncertain orders. Upstream from the CODP all products are produced to forecast; downstream from the CODP all products are pulled by the end user*".

For example, company that utilizes mass customization tools to produce paint might mass produce paint without pigment. Company delivers the unpigmented paint and the necessary pigment powders to its paint distributer. To this point the paint is mass produced and in a state, where its final color is not yet fixed, i.e. not linked to specific customer order.

When customer wants to buy a specific shade of paint and order penetration point is reached, the paint distributor mixes the right amount of pigments to paint and customer receives just the right colored paint on the spot. It is imperative to notice how order penetration point affects the customer's lead time, and according to Olhager (2003) order penetration point's main competitive impact is the customer's lead time.

Order penetration point is closely connected with concept of supply chain process type and often order penetration point is indirectly denoted by the supply chain process type (Olhager, 2003). Different supply chain types identified by Olhager (2003) and the locations of OPP are presented below in figure 3.

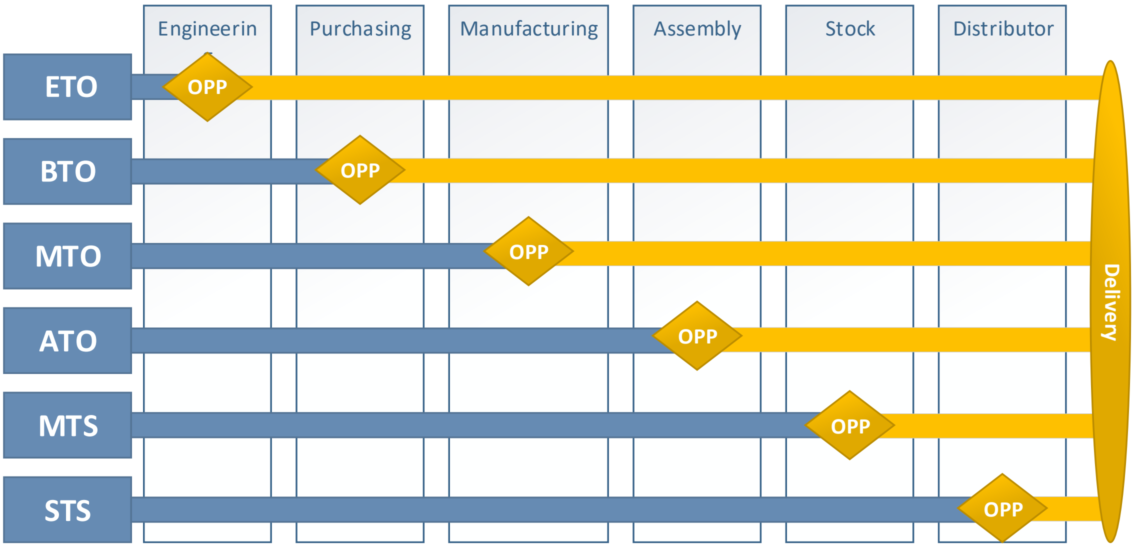

Figure 3: *Supply chain process types and location of order penetration point, adaptation from Olhager (2003)*

In this conceptual image, all the products go through the same supply chain process: product engineering, purchasing of components and raw materials, manufacturing, assembly and delivery. Blue parts of the process line represent operations that are done according to forecast and orange lines represents process parts that are pulled by the customer.

First supply chain process type is engineer-to-order, ETO. In ETO process, order penetration point is located in the product engineering phase. In the literature it is agreed that in ETO supply chain, production is always customized to customer order and the engineering phase is the place where order penetration happens. Companies working with this kind of ETO supply chain are often referred to as being project, craft, one-of-a-kind, design-to-order or engineer-to-order companies. (Gosling, Jonathan, Naim, 2009)

Buy-to-order, BTO, processes links the customer order to product before purchasing phase, make-to-order, MTO, order penetration point is in the manufacturing phase and assemble-to-order, ATO, OPP decides before assembly phase of the product. Make-to-stock, MTS, and ship-to-stock, STS, process' are used for products that are manufactured according to forecast. In MTS process product is in stock waiting for customer order to be linked to it. In STS process goods are shipped according to forecast to distributors and OPP is in the distributors inventory.

Wikner and Rudberg (2005) propose dividing the order penetration point to separate design and production dimensions. These dimensions are detached from each other to grasp the reality in which many project businesses work. Even though company makes one-of-a-kind projects, they can reuse parts of engineering from old projects. Company may also use mostly standard modules to assemble the project. Engineering needed in customer specific parts of the system can be done after order penetration point to derive the product to customer needs, and thus straightforward engineering to purchasing to manufacturing process does not represent reality in many cases. These dimensions are presented below in figure 4.

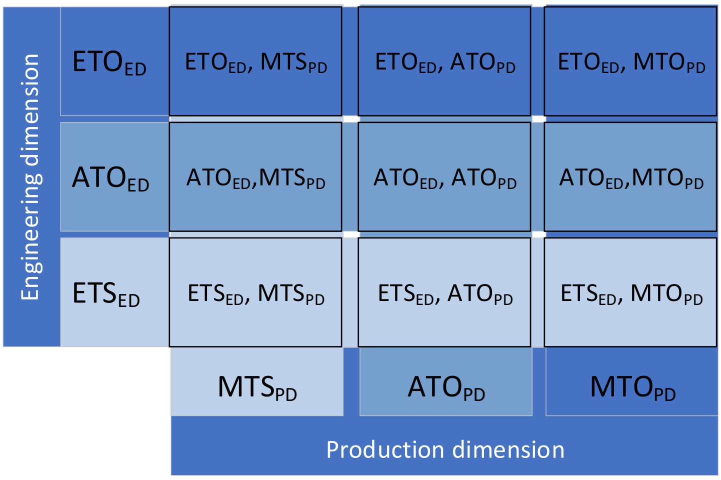

Figure 4: *Engineering and production dimensions of OPP, adaptation from Wikner and Rudberg (2005)*

In figure 4, OPP in engineering is divided to three possibilities: Engineer-to-stock (ETS_{ED}), adjust-to-order (ATO_{ED}) and engineer-to-order (ETO_{ED}). ETS_{ED} represents situation where company has all the required designs ready and can reuse them to fulfill engineering needs of customer orders, ATO_{ED} requires company to adjust something in the available design work to fulfill customer need and ETO_{ED} requires engineering the product from the beginning. (Wikner, Rudberg, 2005)

The production dimension for OPP is also divided to three categories: Make-to-stock (MTS_{PD}), assemble-to-order (ATO_{PD}) and make-to-order (MTO_{PD}). In make-to-stock situation whole production can be done to stock according to forecast. Assemble-to-order can use ready-made standard subassemblies or components to derive the final product according to customer order in assembly phase and in the make-to-order alternative, company manufactures the final product from scratch without making any parts to forecast in the supply chain. (Wikner, Rudberg, 2005)

In order to understand the differences, benefits and shortfalls between different order penetration point dimension combinations, generalized and simplistic delivery process flows for every combination is presented in the figures 5, 6 and 7. Visualizations are divided to three parts: new product development, forecast driven and order driven. Processes including some kind of reusable engineering have new product development, NPD, phase. For example, in adjust-to-order engineering dimension, product platform design is carried out in the NPD phase and design is finalized after the order penetration point. Forecast driven phase consists of operations that can be done according to forecast before the order penetration point. It is clear that without NPD phase, there can't be forecast driven activities as no solution space for product has been defined and there are no designs to follow in production. After the forecast driven phase comes order penetration point and the order driven phase of the delivery starts. Delivery lead time is the time order driven activities take in total before order fulfilment is achieved.

Regardless production dimension process, the production is divided to purchasing, manufacturing and assembly in the visualizations. Purchasing phase consists of procuring raw materials and components for manufacturing and assembly phases. Manufacturing and assembly phases are separated to allow handling them individually. In this context, manufacturing is the initial part of the production process that can be completed with just the platform design ready, without knowing the complete design of end-product. The assembly part of production process continues the initial production done in the manufacturing phase and finalizes the production process according to finalized design.

In the figure 5, processes for make-to-stock production in different engineering dimensions is visualized. In make-to-stock production dimensions, only feasible engineering dimension is engineer-to-stock where end-product is completely designed in NPD phase and all the production operations are done according to forecast. In this kind of process there is no delivery lead time, as customer order can be fulfilled the moment the order penetration happens.

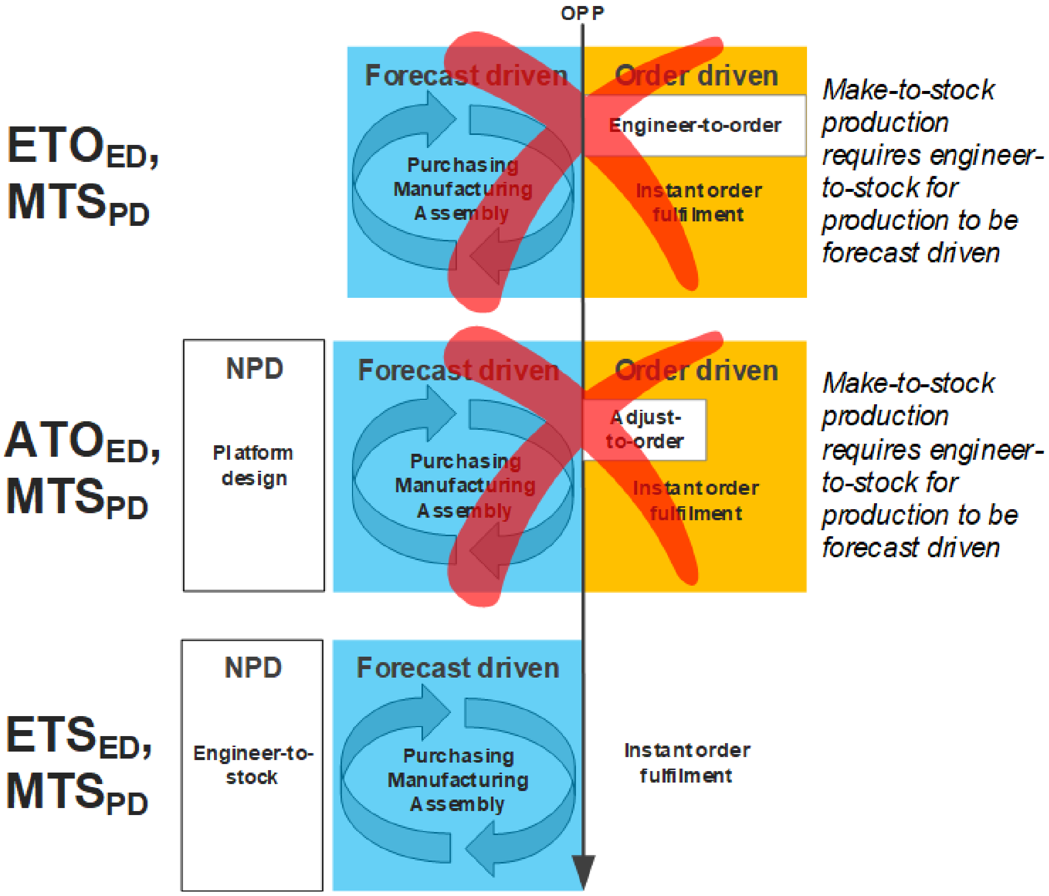

***Figure 5:** Make-to-stock production in different engineering dimensions, adaptation from Wikner and Rudberg (2005)*

Make-to-stock production dimension and adjust-to-order engineering dimension is contradictory, as producing the end-product fully according to forecast before the end product is even designed is impossible. Also, the process for make-to-stock production dimension and engineer-to-stock engineering dimension is contradictory as make-to-stock production carries out all the production related activities before the order penetration point according to forecast, but the design is done from scratch after order penetration point in engineer-to-order engineering dimension. Clearly production cannot make anything according to forecast, as end-product need to first be designed at least partially.

In the figure 6, process for assemble-to-order production in different engineering dimensions is visualized. In engineer-to-stock – assemble-to-order process, product engineering is fully carried out in the new product development phase. Purchasing and manufacturing operations are carried out according to forecast and after the order penetration point, products are assembled to final form. Assemble-to-order production dimension's order driven phase includes possible purchasing phase, if everything could not be purchased according to forecast for one reason or the other.

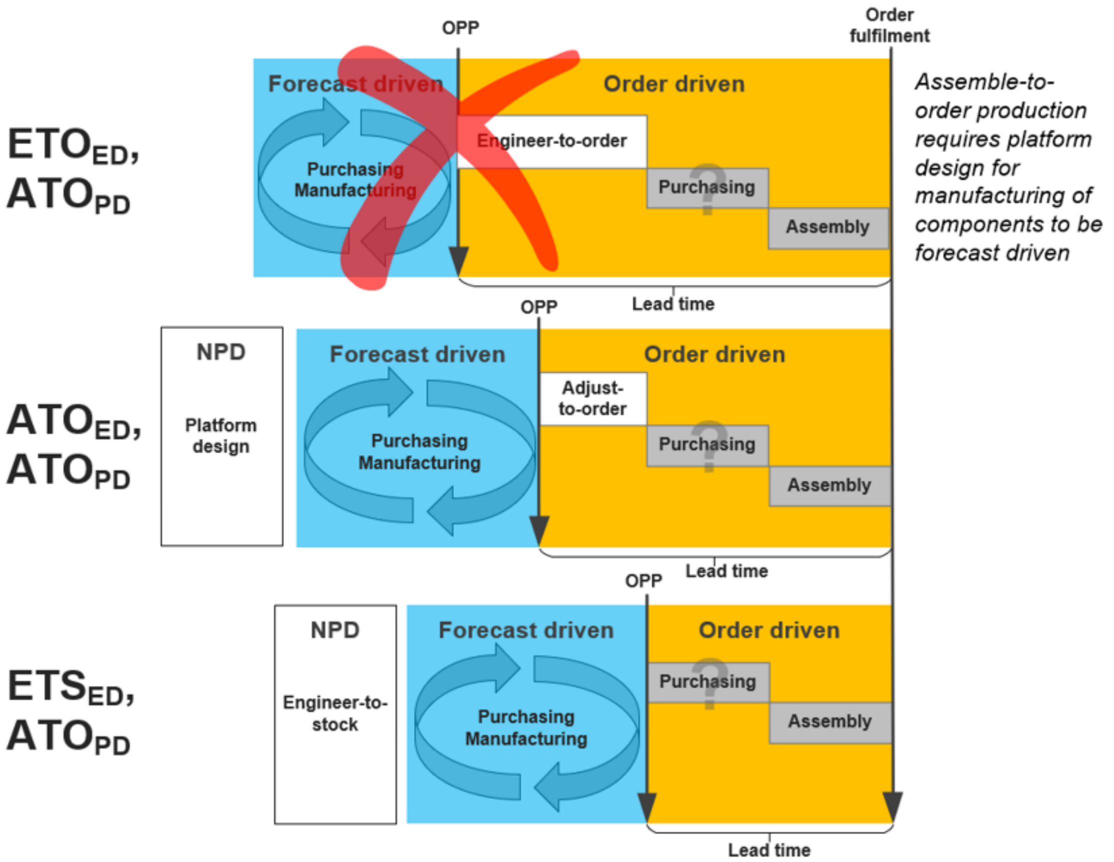

Figure 6: *Assemble-to-order production in different engineering dimensions, adaptation from Wikner and Rudberg (2005)*

Adjust-to-order engineering dimensions combined with assemble-to-order production dimension describes delivery process where platform design is carried out in the NPD phase and part of the production activities are forecast driven. After the order penetration point, platform designs are adjusted to customer order and rest of the production activities are completed according to finalized product design.

Engineer-to-order engineering is not feasible to combine with assemble-to-order production. This is clearly contradictory, as assemble-to-order production completes some production operations according to forecast, but in engineer-to-order process there is no initial designs according to which production could make its forecasted operations.

In figure 7, make-to-order production process is visualized with different engineering dimensions. Engineer-to-stock dictates that all engineer is finished in new product development phase. In ETS_{ED}, MTO_{PD} inventories can be refreshed according to forecast, but manufacturing and assembly processes are started only after order penetration point.

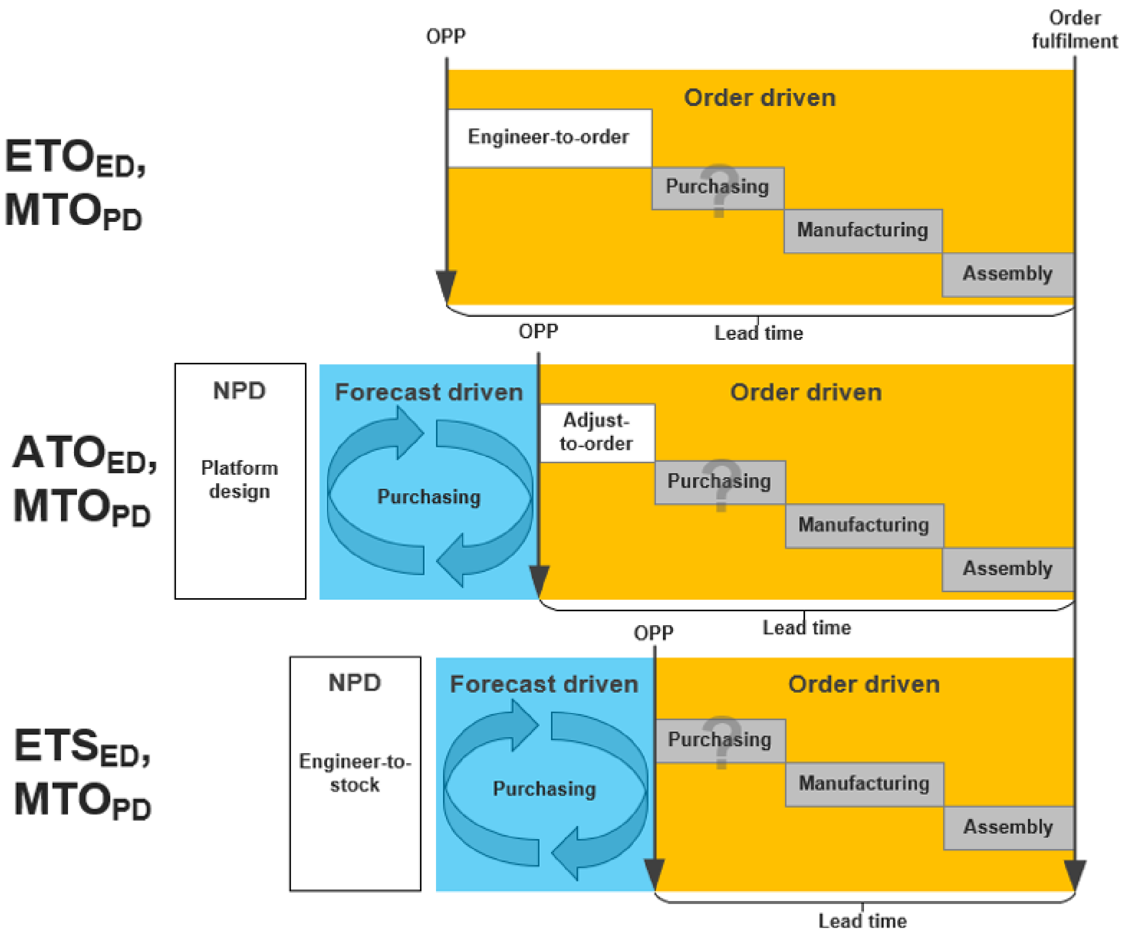

Figure 7: *Make-to-order production in different engineering dimensions, adaptation from Wikner and Rudberg (2005)*

Adjust-to-order engineering process combined with make-to-order production process lead to supply chain process where product has platform designs ready and production can make purchasing to inventory according to forecast. After order penetration point, engineering needs to finalize the design work so production process can start and produce the end product.

Logically it is possible for adjust-to-order phase and production process to start at the same time after order penetration point, if production process is organized so that production can be started according to platform design and final product design is needed only in the later stages of production. For simplicity, this is not visualized in the figures.

In Engineer-to-order – make-to-order process nothing is done according to forecast and all operations concerning the product design or production start after the order penetration point.

The information in figures 5, 6 and 7 is compiled to figure 8 for more understandable and visual explanation of different engineering and production dimension combinations.

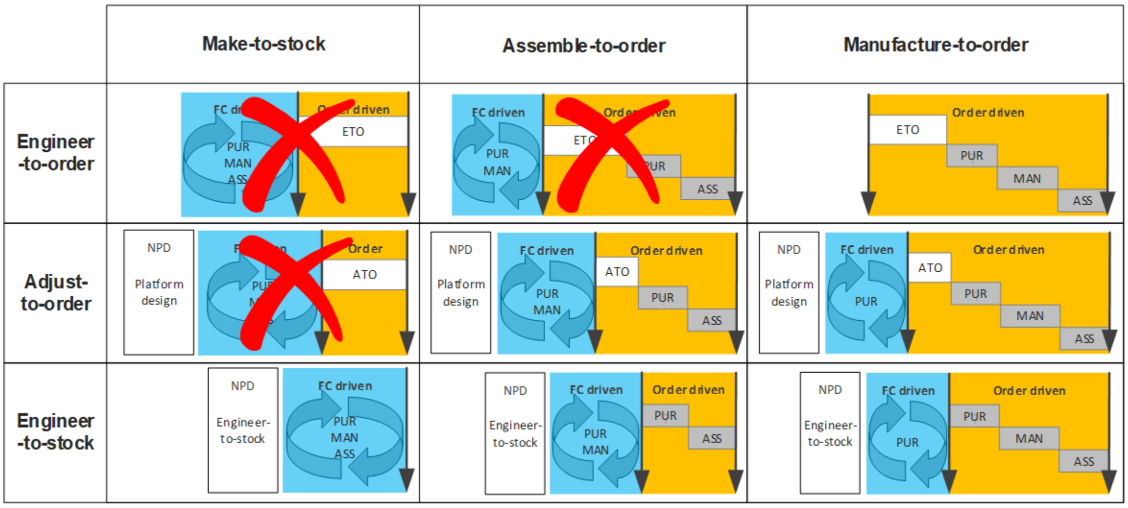

Figure 8: *Visual explanation of different production and engineering dimension combinations, adaptation from Wikner and Rudberg (2005)*

The combination of these dimensions allows more detailed model to study supply chain, than traditional linear order penetration point model (Wikner, Rudberg, 2005). For example, point [ETS_{ED}, MTS_{PD}] represents situation equal to traditional make-to-stock OPP where company manufactures products to stock according to forecast and uses designs that are already created, but situation where engineering is adjusted to order utilizing engineering work done before customer order and production is carried out by assembly from standard modules to fill customer need, can't be described with traditional one-dimensional OPP model.

Shifting order penetration point needs to always be strategically motivated endeavor. Moving OPP forward in the supply chain, postponing OPP, can be done to reduce lead time to customers and increase operational efficiency. (Olhager, 2003) Postponement of order penetration point has been identified as important factor in the pursue of mass customization by numerous articles e.g. Feitzinger and Lee (1997), Kotha (1995), Lampel and Mintzberg (1996), Van Hoek (2001) and Yang and Burns et al. (2004).

According to Gosling (2009)

> "*postponement centres around delaying activities in the supply chain until real information about the market is available*".

Postponement can also be defined as

> "*delaying activities in the supply chain until customer orders are received with the intention of customizing products, as opposed to performing those activities in anticipation of future orders"* (Van Hoek, 2001).

With postponement company can expect to reach shorter delivery time, better delivery reliability and lower costs. While postponement can sound tempting for all companies, it involves risks. When postponing OPP, company needs to rely more on forecasts when manufacturing its products, which leads to increased risk of inventory obsolescence if forecasting is not accurate. On the other hand, if company decides to streamline its product offering to reduce inventory risks, it might drift away from customer by reducing the customizability of the product. (Olhager, 2003)

Shifting OPP backwards, closer to the customer has inverse effects compared to postponement. Company gets better understanding of customer need and enables manufacturing products with better market knowledge, while reducing risk of inventory obsolescence. At the same time company sacrifices the part of the efficiency that producing to forecast can bring and customers must endure longer lead times. (Olhager, 2003)

The most relevant factors affecting the positioning of order penetration point are customer lead time requirement in contrast to total manufacturing lead time, and relative demand volatility. Relative demand volatility is defined by Olhager (2003) as *"the coefficient of variation, i.e. the standard deviation of demand relative the average demand"*. If customer lead time demand is shorter than total manufacturing lead time, company is forced to do some operations according to forecast to fulfill the customer need for lead time or face withering sales. On the other hand, if relative demand volatility is very high, company might have hard time making accurate forecasts on which its operations should be based on. (Olhager, 2003)

Garg and Tang (1997) coin an approach of multiple points of differentiation for order penetration point postponement strategies. In this approach product is gradually differentiated to customer order in multiple differentiation points. This kind of approach can be used for example first manufacturing common components, later differentiating the product to product family and in the last stage differentiating the product to final version. With multiple points of differentiation, company can gradually differentiate the product according to the available market information instead of committing to final product in one differentiation point effectively decreasing the relative demand volatility compared to single-point-of-differentation. (Garg, Tang, 1997)

In article "Design for postponement" (2003), Swaminathan and Lee recognize three enablers of postponement from literature: process standardization, process resequencing and component standardization. Process standardization is the act of standardizing the early phases of the process for different products in the same product line or category and adding the distinguishable features in the later phases. This enables moving the OPP to point where product is differentiated to customer order. Process resequencing refers to reordering the value creation chain so that processes that differentiate the product for customer order are done at the later phases allowing the OPP to be postponed further. Component standardization is closely tied to process standardization and process resequencing, as using standard components shared in product line improves process flexibility and thus supports these activities. (Swaminathan, Lee, 2003)

2.5 Lean and agile management paradigms

After the first discoveries of Lean by academics in early 1970's, Lean has steadily risen to potentially the most discussed management paradigms in history (Stone, 2012). Lean incubated in Japanese car manufacturing company, Toyota, after the second world war when Japanese economy was in ruins and resources were scarse (Modig, Åhlström, 2013, p 71). Demand for wide variety of differentiated cars combined with the lack of resources and Japanese protectionism of domestic car industry pushed Toyota to develop new ways of production that we today know as lean principles. Currently Lean is embraced especially in the high-volume manufacturing industries, like car manufacturing where it originally developed (Womack et al., 1990).

On the other end of the management paradigm spectrum lies Agile. Agile management philosophy aims to reap profits from the market by quickly adapting to new market knowledge and exploiting the opportunities in the changing market. (Naylor et al., 1999a). Agile supply chains also need to be flexible and robust to be able to withstand the constant change that markets force to this kind of supply chain (Naim, Gosling, 2011). Agility can be seen as direct reflection of the firm's ability to gain its competitive edge and perform in terms of time-based competition (Kumar, Motwani, 1995).

Some authors argue that adapting lean concepts like JIT, reduction of suppliers and deeper supplier relationships from high volume manufacturing can be useful in ETO environment, but at the same time ETO markets make many of the high-volume manufacturing management paradigms obsolete (Jahnukainen, Lahti, 1999, Hicks et al., 2000).

Naylor et al. (1999) introduce term called leagile supply chain. In leagile, supply chain is divided to two parts from order penetration point. Naylor (1999) suggests adopting lean principles in the processes before order penetration point as everything is done according to forecast and often low costs are the main driver and using agile operations in the processes after the order penetration point as the main driver is fulfilling the identified customer need quickly. This is also supported by Naim and Gosling (2011) who summarize that agile supply chains embrace the market variation by exploiting the well adapting supply chain as lean aims to rid the variation and create manufacturing conditions that are as stable as possible.

2.6 Synthesis of theoretical background

In previous chapters, general understanding of time-based competition was first established after which focus was shifted to time-based competition in supply chain. Time-based competition is not merely a strategy which sacrifices operational efficiency on the altar of customer, but actually leads to operational excellence as company actively aims to reduce lead time.

First, most impactful ways to reduce lead time, without being forced to modify the product structure, identified by literature was presented. These process improvements were

- factory employee involvement in problem solving,
- re-engineering set-ups,
- cellular manufacturing,
- quality improvement,
- preventive maintenance,
- trustworthy suppliers and
- pull production. (Koufteros et al., 1998)

Then, as this master's thesis is focused on studying evolution of current project product structure towards modular structure, the scope of literature review was extended to consider factory lead impact when moving from traditional product structure to modular.

Mass customization was identified as a general concept that strives to deliver customized products with the price of mass produced ones. Using concept like modularity, company can achieve mass customization. Mass customization was also identified as a way to reduce lead time, but mass customization in itself is not a concrete tool to achieve this.

Modularity is dividing complex problems to smaller, more understandable parts. With modularity complex problems can be solved piece by piece without the need to know how other parts of the larger puzzle work or how they are implemented. With high degree of product modularity, parts of the product can be designed and manufactured independently, assembling them together in the end to form functioning end product.

With modularity, product platforms come to play. Product platform is the base to which modularity builds to. Platform consists of interfaces and subsystems from which derivative products can be easily developed (Meyer, Lehnerd, 1997). Successful modularity and product platform design helps company to achieve true mass customization, as the customization aspect is built in to the product design and the customization can be done with operational efficiency.

Main mechanism affecting the product lead time is order the penetration point, which indicates the point in the delivery process, where individual product is linked to customer order. Characteristic to pre-order penetration point operations is that everything is done according to forecasts, and post-order penetration point operations that everything is done according to customer order.

Wikner and Rudberg (2005) propose two-dimensional model for order penetration point analysis. The model dimensions are order penetration point in the engineering dimension and order penetration point in the production dimension. Different combinations of these dimensions and their simplified processes are visualized in the figure asdf below. Blue parts signify forecast-driven operations and orange parts order-driven operations, which translates directly to factory lead time of the order.

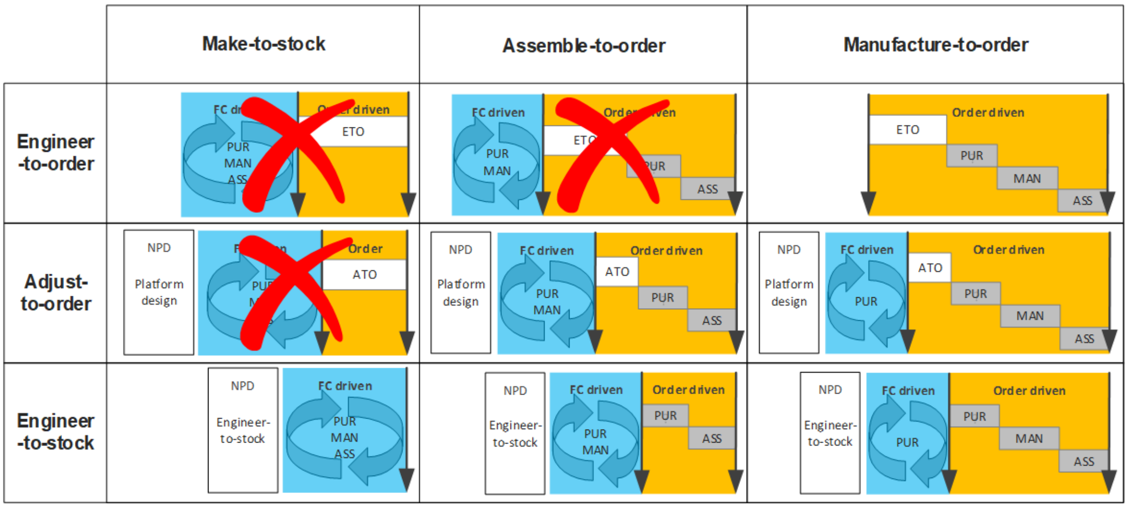

Figure 8: *Visual explanation of different production and engineering dimension combinations, adaptation from Wikner and Rudberg (2005)*

Choosing the right order penetration point requires balancing between delivery lead time and acceptable market information uncertainty. Customer lead time requirement in contrast to total manufacturing lead time and relative demand volatility are fundamental variables to consider when choosing the order penetration point. Garg and Tang (1997) propose a concept of multiple points if differentiation, where product is gradually differentiated to customer order in the supply chain. This way as product moves forward in the supply chain, the differentiation increases and at the same time as time passes, the company has more market information to act and decide to which direction the product should be differentiated.

Challenge of mass customizing in companies that currently operate some form of engineer-to-order supply chain is often in defining the right architecture. Architecture needs to cover sufficient amount of possible customer needs and still reach meaningful amount of product commonality. To achieve this, a certain amount of commonality must be found in the customer needs and clever design decisions must be made to be able to encapsulate these commonalities in to the architecture. (Haug et al., 2009) If modular architecture design is successful, company can experience increased profits as using standardized modules to create end-product that is tailored for customer order has been recognized as one of the most efficient ways to reach sufficient product customization (Yang et al., 2004). Also, the standardization and commonality created by modularity support the enablers of postponement; process standardization, process resequencing and component standardization (Swaminathan, Lee, 2003), thus allowing company to postpone the order penetration point and reap the resultant benefits.

Olhager (2003) notifies that as OPP works as a decoupling point for upstream and downstream operations in supply chain, it also gives clear guidance on what kind of performance to focus on in different parts of supply chain. Process parts before the order penetration point need to focus on efficiency and supplier collaboration, as main focus of processes after the OPP is the customer. (Olhager, 2003) To achieve optimal performance in both before and after the OPP, so called Leagile supply chain has been proposed. In this kind of supply chain operations before the OPP apply principles of Lean philosophy and operations after the OPP apply Agile philosophies to serve the customers in the rapidly evolving market environment. (Naylor et al., 1999b)

Below in figure 9 is presented a synthesis of addressed theory concepts and their most notable connections.

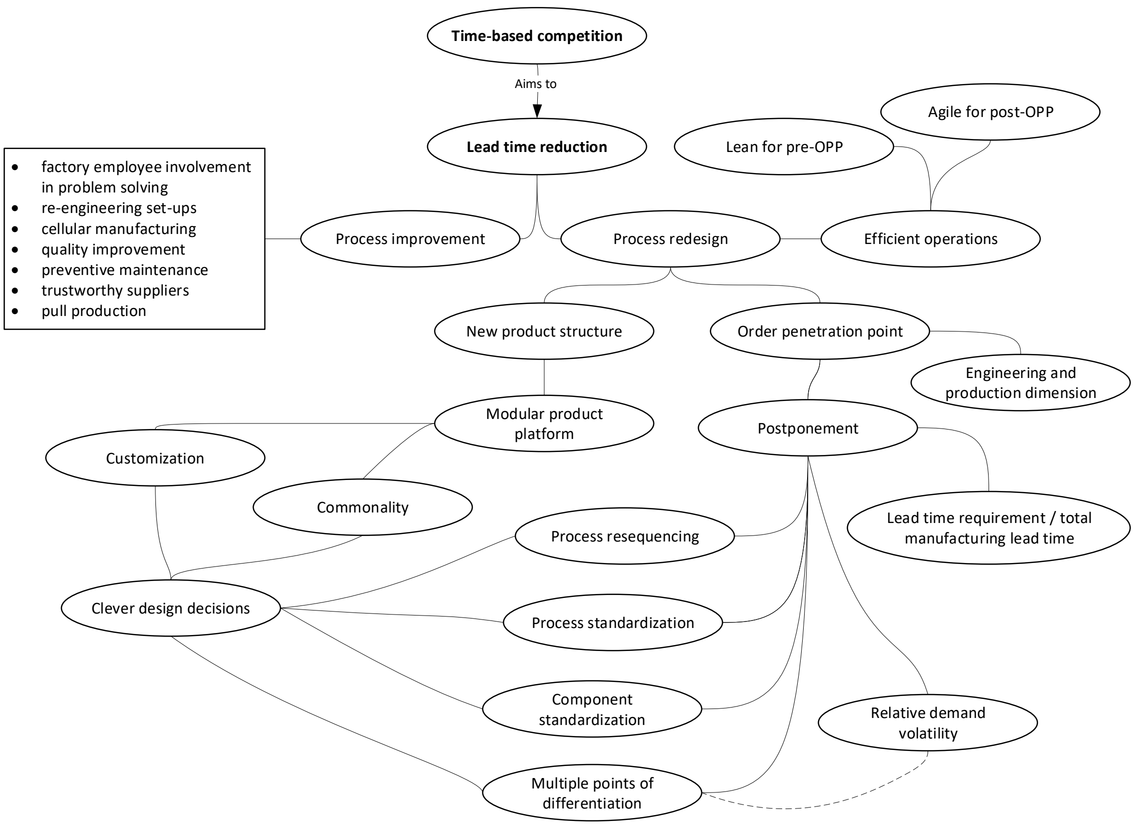

Figure 9: *addressed theory concepts and notable connections*

Modular product platform and design decisions concerning its architecture can be seen as factory lead time defining. Design decisions made in the modular platform design phase impact the range of possibilities company has in order to postpone the order penetration point, and thus create basis for lead time reduction and time-based competition in supply chain.

3. CURRENT SYSTEM DELIVERY LEAD TIME

In this chapter, the data used for current system lead time definition is first introduced. Then in separate chapters, detailed delivery process for lead time definition is specified, design, assembly and testing lead times are deduced from the ERP system's project cost transaction data and purchasing process lead time is defined by analyzing the ERP system's purchase order history data and combining it with available data about agreed delivery times with suppliers. In the end of this chapter, all the outcomes of these individual analyses are combined to Gantt chart presenting the current factory phase delivery process lead time.

3.1 Data remarks

Main data sources of this study are Fastems' enterprise resource planning, ERP, software's operational databases and conducted personnel interviews. Personnel interviews were used to explore for a meaningful model for lead time estimation, to map the dependencies in the factory phase of delivery process, to define the test times for subsystems and to triangulate the process part lead time results concluded from ERP system's data. Archival data from company's ERP system was used to estimate the lead times for individual factory phase's delivery process parts.

Two different ERP data exports were made for this study. First data export was for estimating design, assembly and testing lead times and for defining dependencies between different subsystems and processes. It includes all the transaction data available for MLS projects that were started after 1.9.2014 and completed before 14.7.2016. Start date of the included timespan is due to activity structure change during 2014 and it was estimated that all projects started after 1.9.2014 are using new activity structure.

Activity structure is used to group and classify transactions automatically for different parts of the project. For example, cost transaction from purchase order invoice for material used in loading station moving would be classified to activity LSM_P, short for loading station moving purchases. Activity classification is a key factor in the success of this study, as it is possibly the only way to easily recognize the subsystem that the transaction is connected to.

Another important transaction dimension is transaction type. Possible transaction types and explanations are listed in table 2.

Table 2: *Transaction types and explanations*

Transaction type	Explanation
DEAUTOM	Automation design
DEMECH	Mechanical design
PUMAT	Material purchase
PUWORK	External resources work for assembly or installation
WOASSEMBLY	Assembly work, internal Fastems resources
ACCRUAL	Accrual for warranty and scrap costs
DECOMM	Design related to system commissioning
DEDOC	Documentation
DEPRO	Project management
DESOFTW	Software design
INCOME	External income from customer
INT_INCOME	Internal income from transfer pricing
INTERNAL MARGIN	Internal margin
PUTRAVEL	Travelling expenses
WOINST	Installation work, internal Fastems resources

Second ERP data export was used to estimate purchasing time for different subsystems. Data export includes all the purchase order lots for projects in the first transaction data export. This data did not include purchases to stock.

Both data exports were implemented using SQL query to ERP databases and results were saved to Microsoft excel file for further processing. SQL queries were made in collaboration with company's ERP database specialist to ensure data integrity.

Lead time estimation processes introduced in coming chapters were designed to reflect lead time of regular system defined earlier. This sets some challenges for interpreting the data sample, as the line between regular system and special system is vague. All systems are engineered to customer order and defining unambiguous specifications for distinguishing regular from special system is very challenging. Because of this, researcher has used his own judgement to exclude projects from data sample in individual analyses, if the project's data differs significantly from bulk of the data.

3.2 Detailed delivery process description

For current system's factory phase delivery process lead time estimation, the current process was mapped from interviews with experts in each area. Interviews concerning the process mapping of current delivery process were:

- Design process: Teemu Jaakkola, Head of mechanical and electrical design department, conducted on 22.12.2016

- Design process: Pertti Lukkari, Head of software development department, conducted on 12.12.2016
- Purchasing process: Jenny Jyrinki, Team leader of Purchasing team, conducted on 21.12.2016
- Assembly process: Operations planning interview with Kari Molarius and Hannu Leinonen, conducted on 20.12.2016
- Assembly process: Work planning interview with Maiju Lahti and Sten Lundberg, conducted on 15.12.2016

To be able to define lead time for complete system that consists of multiple system parts and processes, it is necessary to map implementation order dependencies of those parts and processes. Dependency in this study's context is defined as follows:

System part or process of which start, or completion is dependent on other process' or subsystem's status

As a result of interviews, detailed process description suitable for lead time estimation of current system, was formed. This process description is visualized below in figure 10 with identified process dependencies as defined above. Explanation of the delivery process is presented after figure 10.

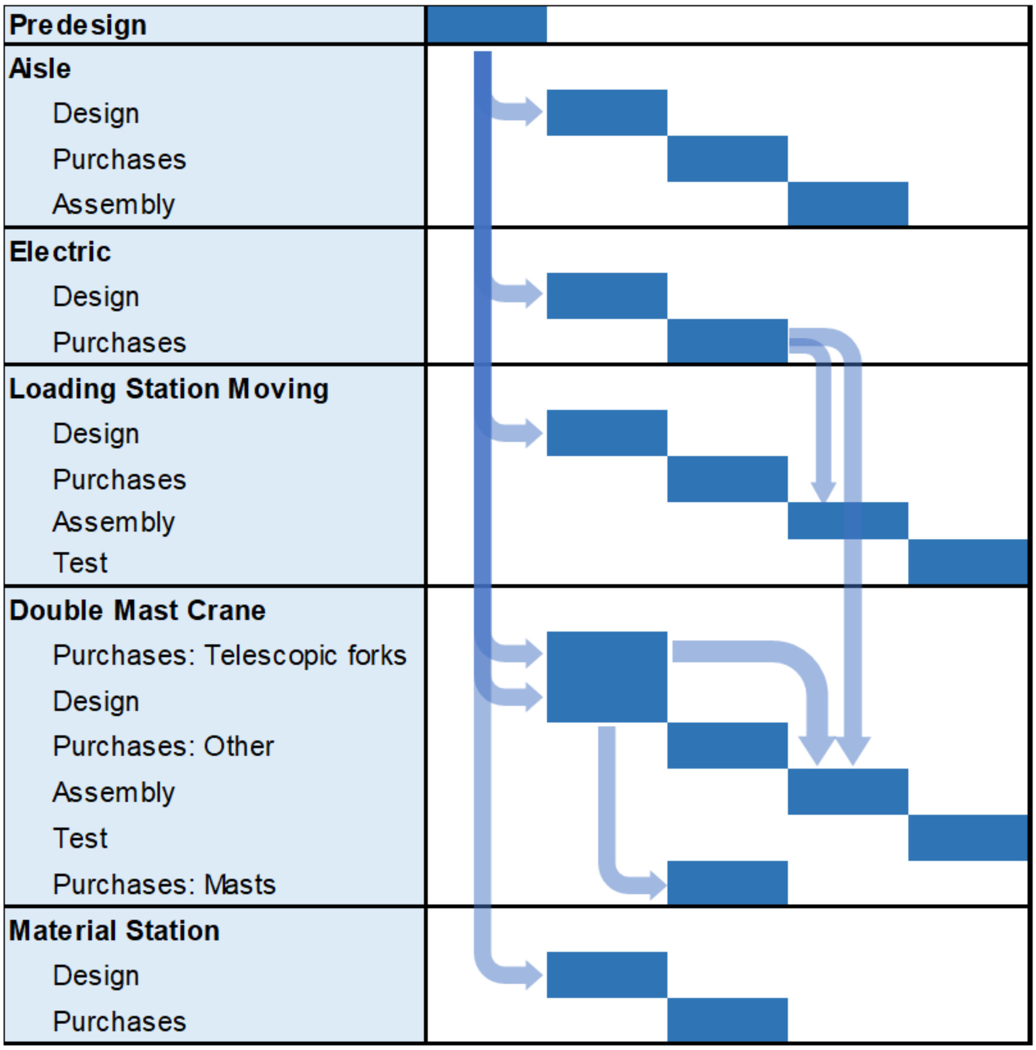

Figure 10: *Current factory phase delivery process and identified dependencies*

Every system delivery process is different and creating a general model to be used in this study requires some simplifications compared to reality. Under delivery time pressure from customers and order backlog, organization has evolved so that project deliveries are planned individually for project needs and different delivery process phases might overlap on some parts of the project. To reconcile some of the lead time estimation error arising from imperfect delivery process model, the most notable and concurring instances of overlapping of process phases are considered in the model. Most notable example is the process of designing and purchasing of telescopic forks in advance compared, to rest of the system due to potentially very purchasing lead time telescopic forks.

The project delivery process concerning this study starts after the sales phase has been completed and order confirmation has been received. To simplify, all initial information needed for design process is assumed to be clarified in sales stage, even though reality is that part of the required initial information is still unclear in predesign phase.

Predesign phase is separated to its own phase for purpose of this study. Predesign phase partially overlaps with the sales phase as some predesign is already done in end of the sales phase. During predesign phase no subsystem design is done and predesign phase is a prerequisite to subsystem design activities, as visualized in figure 10 with blue arrows. During predesign phase, parts that affect the design of the whole system are designed. Most notably these include the design of load handling and lead engineering activities to extent that is needed to start subsystem designs. Load handling design consists of designing how the customer's workpiece pallet will be handled and includes all the physical interfaces that the machining pallet is in contact with during its time in the system. Lead engineering consists of designing the system at aggregate level, deciding what parent models of sold subsystems are used and how they should to be modified for the project. Both lead engineering and load handling design continue after pre-design in conjunction with subsystem design activities, but they are not presented in the figure 10 by themselves, as they are thought as a part of subsystem design activity.

Subsystem specific processes start after predesign is completed. Individual system subsystems can be designed as separate entities and all needed input data for design phase is created in predesign phase.

Design process at Fastems is divided roughly to three categories: mechanical, electrical and software design. Mechanical and electrical design are closely tied to project delivery process, unlike software design process which has more leeway. This originates from the fact that in Fastems' project delivery process, no phase concerning this study is dependent from software design's output except testing, which is done at the end of process that this study is examining. Software design's team leader stated in an interview that software design will not belong to the critical path of project delivery process in standard deliveries as software architecture for standard systems is already highly modular and requires only minimum effort from software design per delivered system. Because if this, software design will not be examined further in this study as it is not expected to impact the project delivery process lead time.

Most of the subsystems have the same basic delivery process. In the basic process, subsystem design can start after pre-design is finished. When subsystem design is ready, purchases can be done and after materials have arrived the assembly phase can begin, if assembly is needed. Some subsystems include testing phase which can start after assembly is ready.

Exceptions to basic subsystem delivery process are Double Mast Crane and Loading Station Moving. Double mast crane includes telescopic forks which have long purchasing lead time. Telescopic forks are specified in predesign load handling phase which allows their purchasing to start immediately after predesign phase has ended. Double mast crane also includes masts that have long purchasing lead time. Masts can be purchased after subsystem design is ready, but they are not needed in assembly phase as they are used only for testing at the factory. Double mast crane and loading station moving require subsystem activity “Electric” purchases to be delivered before assembly can begin as these subsystems include electrical cabinets that are needed in their assembly phase. Storage rack requires only purchasing phase, as layout design of is done already in predesign phase and storage is not delivered to Fastems, but straight from supplier to customer site, where supplier assembles the storage.

After individual subsystem activities are ready, everything is packed and sent to customer site where actual system is put together. In some cases, factory acceptance test, FAT, is required by customer, where system is assembled and tested at Fastems factory. In this study we focus on cases where FAT is not required, and system is assembled and tested at customer sit

3.3 Design, assembly and testing process lead times

Design and assembly lead time estimation was implemented with same methodology due to similarities in design and assembly hour bookings for projects. Desired output from this was lead time estimates for design and assembly processes for different subsystems.

Lead time estimation was done by studying cost cumulation over time from different transaction types to subsystem activities. Design lead time was estimated according to mechanical and automation design cost cumulation over time and assembly lead time was estimated according to assembly work cost cumulation over time.

Transaction data includes transaction’s value date, which specifies to what date the transaction is booked to. For lead time estimation, every transaction’s days passed from corresponding activity’s start time was calculated and added to transaction row data. This was implemented by writing Microsoft excel VBA macro that selects project-activity-transaction type combination’s first transaction date, deducts it from every corresponding project-activity-transaction type transaction’s value date and saves the result to new column. This result shows how many days have passed since the first transaction to that transaction’s project-activity-transaction type. Transactions are then classified to one-week bins: first week bin contains days 0-6, second bin contains days 7-13 and so on. By studying these bins, it is easy to determine how much cost transactions have realized during each week after the start of corresponding project-activity-transaction type combination.

This normalization makes it possible to study weekly activity-transaction type cost cumulation from multiple projects at the same time and estimate activity-transaction type lead time for regular delivery project. Example can be seen in figure 11, where sample’s data is illustrated for MLS-MDR type projects, double mast crane activity and transaction type assembly work.

In the figure 11, on the horizontal axis we can see how many weeks have passes since the assembly work of Double Mast Crane has started. The vertical, cost cumulation, axis presents the amount of assembly work done each week. The different legend colors present different delivery projects. As the time dimension of the data has been normalized as defined before, it is possible to analyze these different projects in the same figure. The benefit of analyzing multiple projects in one figure is that with single project, data can be heavily skewed, but as we increase the project count in the sample, we reduce the impact of one skewed project and the form of graph will start to approach the average projects cost cumulation graph. By analyzing these cost cumulation graphs with princibles defined below, we were able to define the normal process lead times for design and assembly process parts.

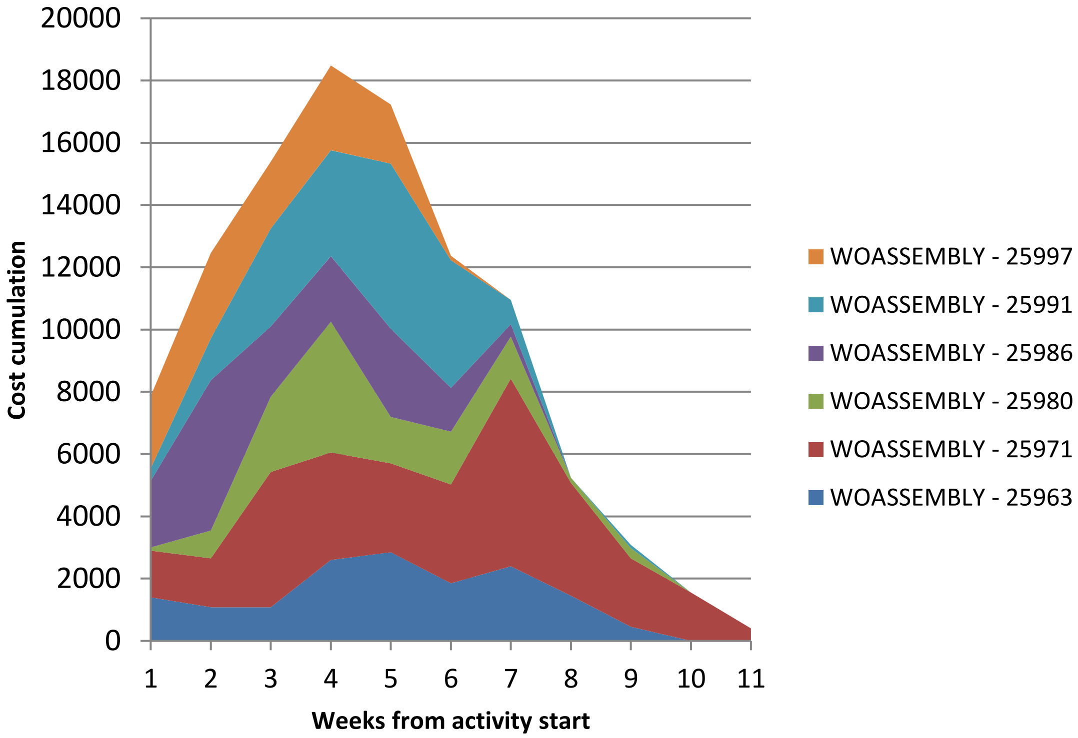

Figure 11: *Weekly cost cumulation for MLS-MDR double mast crane assembly work*

Risk of researcher subjectivity and bias is the most imminent in the actual lead time estimation stage of the process for design and assembly lead time. Normal lead time for activity-transaction type is determined by studying corresponding activity-transaction type graph, as seen in Figure 4, and making an educated estimate of the normal lead time. Most notable factors when estimating the lead time from the graph were:

- Normal lead time is
    a. the most common lead time for the projects in the sample or
    b. lead time that can be in other way argued to be normal by studying historical lead times.
- Projects that differ significantly from bulk of the projects should be discarded from current analysis.

- Projects with long and thin start or end tail should be discarded from current analysis.
- Assembly work includes hour bookings for testing phase which is seen as lower hour cumulation in the end of the assembly work. This thin end tail is not considered to belong to assembly phase, as testing lead time is examined separately.

Design and assembly lead time was estimated according to above process for every subsystem in the research system scope.

The testing phase lead time for Double Mast Crane and Loading Station Moving was defined in the work planning interview with Maiju Lahti and Sten Lundberg, conducted on 15.12.2016. This was done, because testing lead time could not be extracted from the history data, as explained above. Also, the workshop managers in the interview stated that the normal testing time for these subsystems is quite stable.

Definition of predesign lead time was in part different compared to subsystem design and assembly lead times. Visualization of predesign phase is given in figure 11, where data from 26 finished delivery projects is summarized in one graph. By looking at the weekly cost cumulation of load handling and lead engineering, which are both part of the predesign phase, we can see that they dominate the first three weeks of project's weekly cost cumulation. In the figure 12 we can also see that subsystem design activities start around week four of the project. This is the point where predesign is defined as finished, as after this the individual subsystem design processes have historically started. Thus, we can define that predesign phase's normal lead time is three weeks.

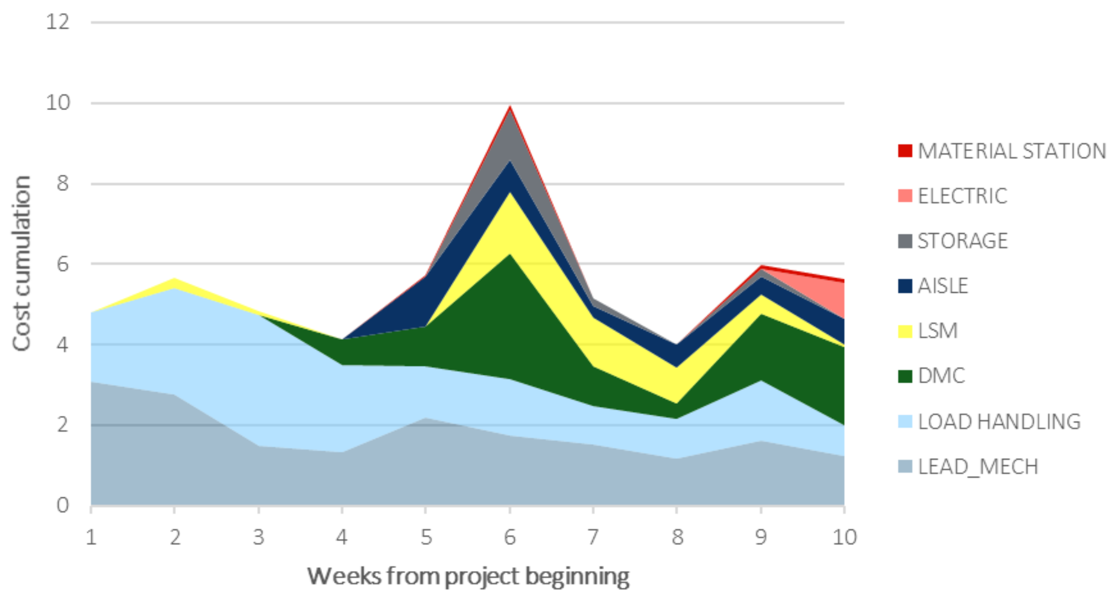

Figure 12: *Weekly cost cumulation of predesign and subsystem design activities*

The design, assembly and test lead times were estimated according to process described earlier in this chapter. The results are gathered and presented below in table 3.

Table 3: *Design, assembly and testing lead times in current system*

Object	Lead time in weeks		
	Design	Assembly	Test
Pre-design	3	-	-
Aisle	1	1	-
DMC	2	5	2
Electric	5	-	-
LSM	3	5	1
Material station	2	-	-

3.4 Purchasing process lead time

In this study, purchasing lead time is defined as the time between purchase order creation and receiving of ordered goods It should be noted that this study is interested about the shortest lead time that can be consistently achieved, so unnecessary lag in lead times should be eliminated. This becomes important when studying processes that are not in current critical path of the project delivery process, as those process parts might have realized with significantly longer lead times than actually achievable by the process.

Purchasing process starts after design is ready and work order has been created. Work order creates automatically material reservations and purchase proposals are created based on material reservations. Typically work order is created at the same day that design is completed, and new purchase proposals are automatically created the next morning. In purchasing lead time estimation, it is assumed that after design is completed, purchasing can start the next day. There is lag time between purchase proposal creation and purchase order creation, because purchasers tend to wait and make larger orders for suppliers rather than make single batch order immediately after purchase proposal is created. This lag is not taken into account when considering the purchasing lead time as it can be eliminated from the process if it is in the critical path of the system lead time. Purchasing process and its predecessors are illustrated in Figure 13 below.

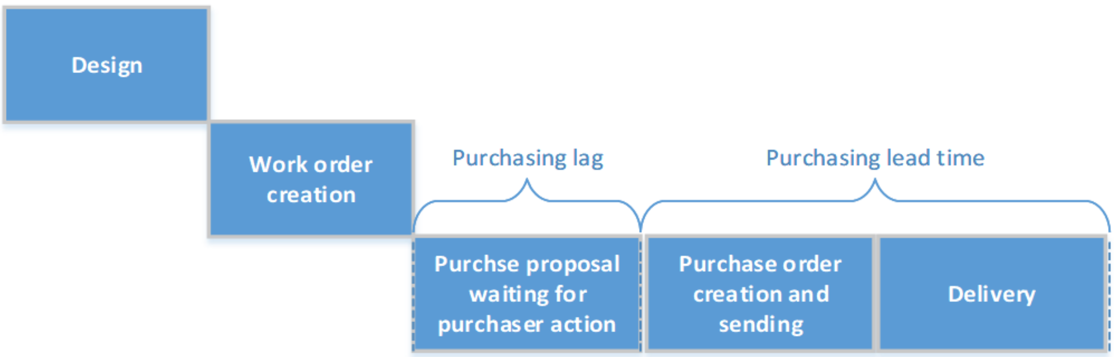

Figure 13: *Purchasing process and its predecessors*

Purchasing lead time estimation was done by studying purchasing lead times for items that were ordered for projects in the transaction data sample. Stocked items were not of the interest here, as it is assumed that stock control levels are adequate, and items can be picked from the stock without purchasing lead time.

Lead time analysis in this study is conducted in the subsystem delivery process level, as presented in earlier in figure 10. For this purpose, purchasing lead time is determined for individual subsystems. It is assumed that the purchases for subsystem can be started at the same time and purchases must be received before subsystem assembly can begin. Because of this, the purchasing lead time is determined by the longest purchasing lead time for corresponding subsystem. Double mast crane masts and forks, and storage system are the exception to this assumption and their lead time impacts are addressed separately.

The assumptions when examining subsystems purchasing lead time are explained below. In this context subsystem group is defined as group of subsystems that are mechanically so similar that they are named with common subsystem name. Example from this kind of subsystem group name is loading stations moving, LSM.

1. Subsystems with same function can be identified from their subsystem activity name.
2. Subsystems with same function have similar mechanical structure – difference is minor and caused from tailoring the subsystem for customer needs.
3. Items with same mechanical parent model or similar function in the subsystem are named similarly.
4. Items with same functionality in one subsystem group are mechanically similar enough to assume they have the same purchasing lead time.
5. Item’s purchasing lead time is its average purchasing lead time.
6. Subsystem’s purchasing lead time is the maximum purchasing lead time of its items.

Following above assumptions, it was possible to define purchasing lead time for every subsystem in the study’s system scope. First the lead time was calculated for every purchase order lot in the data sample. Lead time was calculated by deducting the purchase order lot creation date from the purchase order lot receiving date. Purchase order lots were grouped by subsystem activity and in the subsystem activity groups the purchase order lots were grouped by item name. Grouping was done on item name level to recognize items that have recurring use and to group items together that have same function in the system. Grouping could not be done by item identification number, as item with same general function in system might have multiple different versions and so multiple item identification numbers in the ERP system.

For every subsystem – item name group, the sample's average and maximum purchasing lead time was calculated. Item groups that had sample size of less than three were ignored to omit the items that don't represent the normal system in this study, as they supposedly are related to special customer needs that are not concurring. From every subsystem maximum of 5 item groups with longest average lead time were chosen for closer inspection. If subsystem – item group average and maximum lead time had large difference the purchase order which had the maximum lead time was analyzed and decided case-by-case if it was a representative data point or should it be discarded from sample. To ensure credibility of results, subsystem – item name purchasing lead times were then triangulated by going through them in a meeting with this study's company steering group. Then purchasing lead times for different subsystems were listed according to the maximum purchasing lead time of its item components.

Realized purchase lead times do not always reflect the shortest possible lead time. This can happen for example when item's purchasing phase is not in the critical path of the project and there is no pressure for short purchasing lead time. In this kind of scenario purchaser tends to send the order to supplier well before the requested delivery time to give the supplier some leeway in its production planning activities.

Fastems purchasing department maintains a list of minimum delivery lead times negotiated with suppliers for most common subsystems. Realized purchase lead times were compared with the purchasing department's list of negotiated delivery lead times and possible slack was removed from the realized purchasing lead times. This comparison gave preliminary insights on what subsystems are currently hindering the project delivery process as some of the realized purchasing lead times were shorter than the shortest possible lead times negotiated with suppliers, which implicates continuous delivery time pressure for some subsystems' component suppliers. As a result, a list of minimum purchasing lead times for different subsystems was generated.

Purchasing lead times specified, according to process defined earlier in this chapter, are presented in table 4 below. Realized column shows the results from examining the actual purchasing lead times of delivered purchase orders for different subsystem components along the sample size of purchase orders examined per component. The longest lead time of components is chosen as a realized lead time of the corresponding subsystem. In "Negotiated" column purchasing times for corresponding subsystem agreed with suppliers by purchasing department are presented. The last column shows the minimum of realized and negotiated lead times as the minimum purchasing lead time of subsystem in weeks. The minimum purchasing lead times presented in the table 4, are the purchasing lead times that are used for current system lead time definition, as they are the shortest normal purchasing lead times that are available according to data analyzed in this chapter.

Table 4: Subsystem purchasing lead times in current system

Subsystem	Realized		Negotiated	Minimum
Component	Lead time (w)	Sample size	Lead time (w)	Lead time (w)
AISLE	**11,8**		**6,0**	**6,0**
DRIVE RAIL	8,9	24		
DRIVE RAIL WELDING	11,8	9		
DMC	**6,8**		**8,4**	**6,8**
FRAME	6,2	49		
GEAR MOTOR	6,8	24		
MAST	**7,5**	**34**	**8,0**	**7,5**
TELESCOPIC FORKS	**10,1**	**17**	**6,0**	**6,0**
MATERIAL STATION	**9,2**		**9,4**	**9,2**
CHAIN CONVEYOR	9,2	5		
ELECTRIC	**8,3**		**5,0**	**5,0**
CONTROL PANEL	8,3	16		
LSM	**7,8**		**7,4**	**7,4**
BASIN	6,6	21		
COVER PANEL	7,8	21		
STORAGE			**10,0**	**10,0**

Masts and telescopic forks are divided to their own subsystems in purchasing lead time analysis, as masts are not needed at the start of Double mast crane assembly and telescopic forks are ordered right after the pre-design phase's load handling design is ready.

3.5 Result of current system lead time definition

Subsystem and project phase dependency results are integrated to figure 14 where the results of this chapter are gathered and presented as a Gantt chart which represents the minimum delivery lead time of this study's system scope. The dependencies are marked with arrows and they are always finish-to-start dependencies.

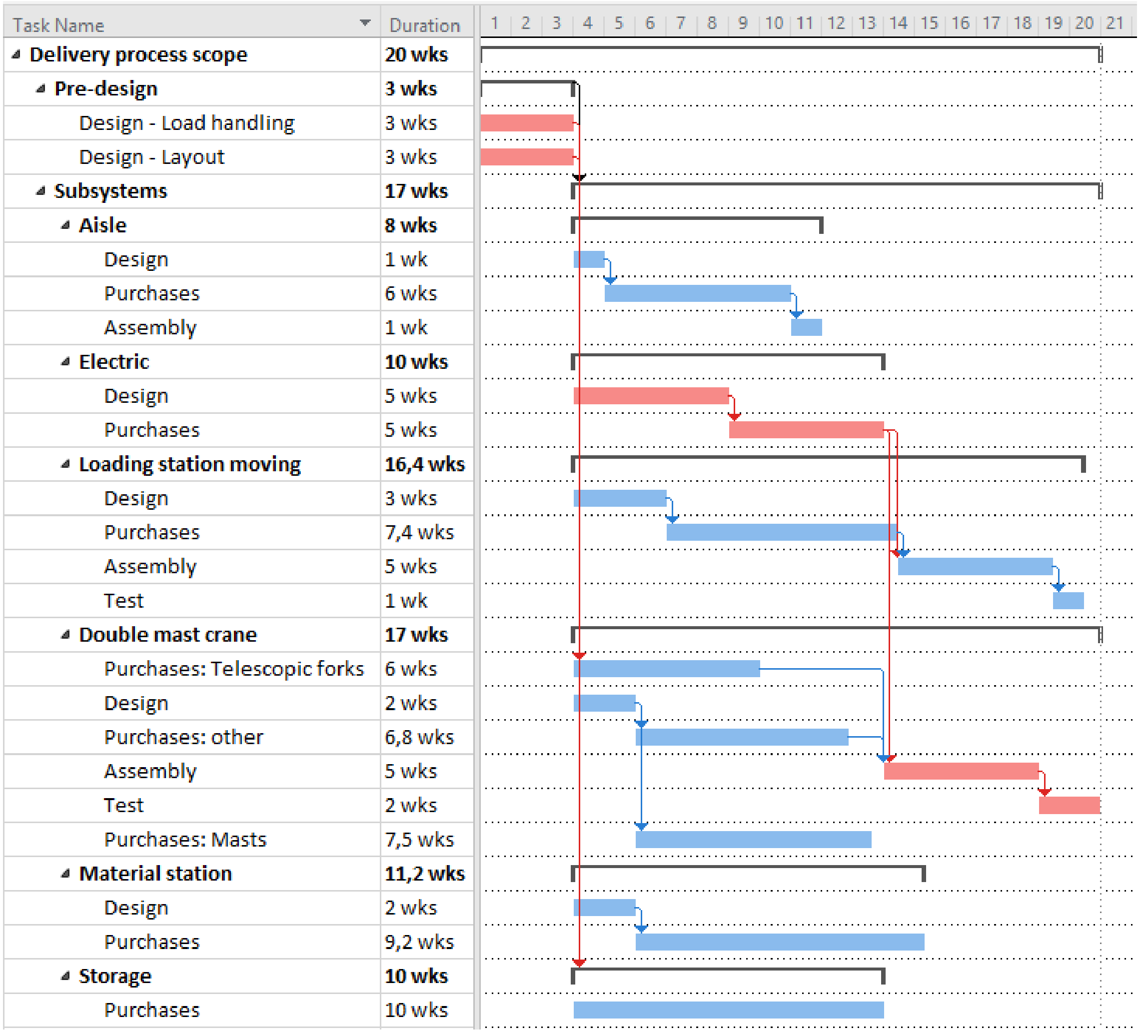

***Figure 14:** Gantt chart of current MLS delivery lead time composition*

The normal factory phase lead time from start of predesign process to end of production for investigated system scope is 20 weeks. Critical path of project implementation is Pre-design – Electric design – Electric purchases – Double mast crane assembly – Double mast crane test. The tasks on critical path are marked to figure 14 with red.

The Gantt chart shows that the schedule for Double mast crane and Loading station moving are both very rigid and with normal deviation in delivery process they both should be considered as critical tasks concerning the project schedule.

4. MODULAR SYSTEM DELIVERY LEAD TIME

4.1 Modular system structure – what is defined

The lead time simulation of modular system structure in this study is based on Fastems' system module map and it has been created in the MLS modularization project. The module map includes exhaustive mapping of system modules currently in the modularization project scope.

Module map is formed as a tree structure where the whole system entity is the main branch as seen in figure 15 below. System is divided to four groups – load handling, transfer and storage, loading cell and electrical interface. These groups are divided to system level components which are almost equivalent to subsystems of current system studied in last chapter. Used system level components decide the broad system functionality – the right system components are chosen for every delivery according to what functionality has been sold to customer. Most of the time system component is one functional and mechanical entity in the system.

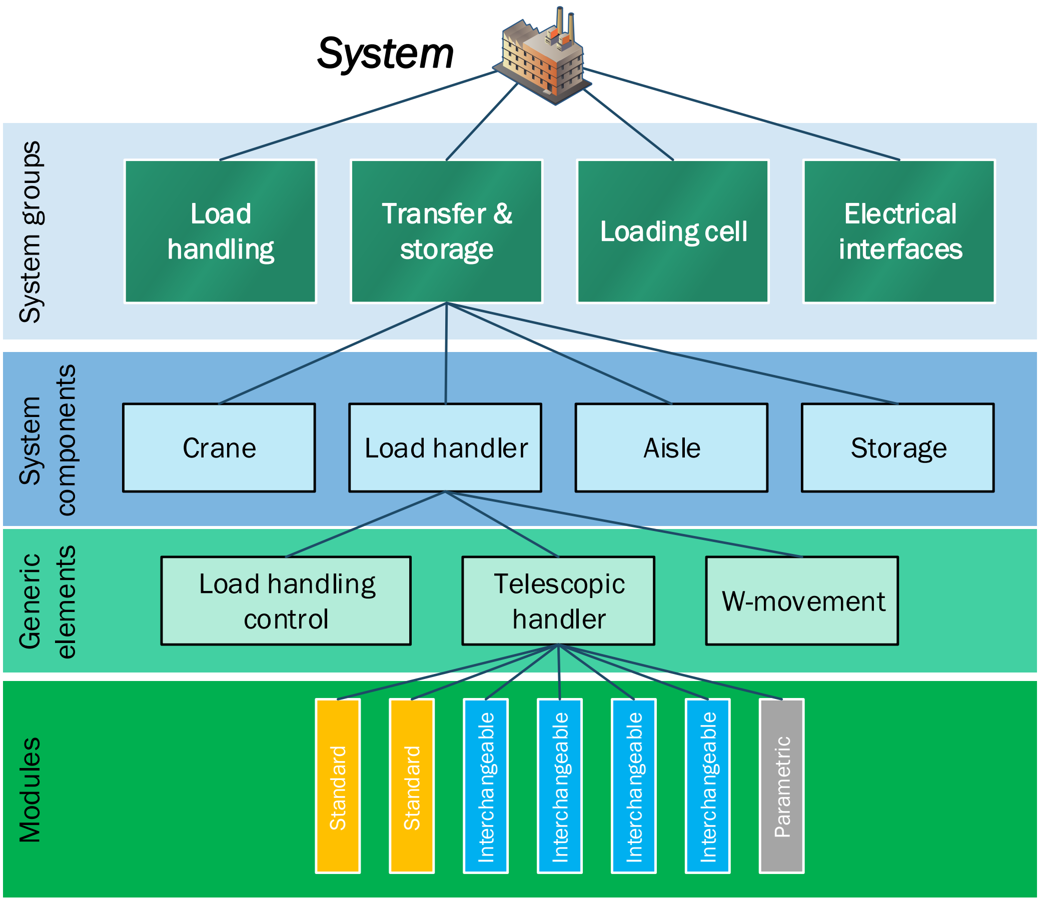

Figure 15: *Tree structure of module map*

System level components are then divided to generic elements which dictate the detailed level functionality of the system level element. For example, pallet loading station is a system level component and generic elements that can be chosen for pallet station are rotation movement, drive movement, tilting movement, lifting movement, pallet table, hydraulics and pneumatics. Pallet loading station functionality that is sold to the customer can be achieved by combining these generic elements which add functionality to system component.

The most detailed level of module map is the actual modules. Modules are used as a building blocks to form functional generic element and every generic element has predefined modules.

Modules are divided to five categories according to the level of standardization the module has. One module category is also reserved for the optional modules which can be used to fulfill some specific customer need but are not always required. These categories and are presented in table 5 below.

Table 5: *System module types and use according to Fastems module map (Aalto, Tanskanen, 2016)*

Module type	Use explanation
Standard	If generic element is chosen, this module is included in the system
Fully interchangeable	If generic element is chosen, one of the alternative modules is included in the system
Parametric	If generic element is chosen, module is included to system with predefined parameters that can be varied according to customer need
Add on - option	Optional module
Delivery specific	If generic element is chosen, this module is included in system and need to be designed according to the customer need

To elaborate the sentiment of above module types: **Standard** modules have standardized structure. Standard module is always added to system if its parent structure is added to the project delivery scope. **Interchangeable** modules have predefined standard alternatives from which to choose from, but no design efforts are needed. **Parametric** modules have predefined parameters which can be adjusted by designers according to customer needs. **Add-on – options** are delivery specific modules that are engineered to order, but they have standardized interfaces to other modules and physical space restrictions. Last module group is called **delivery specific**. These modules are always tailored to customer needs by engineered-to-order process and no hard design restrictions apply to this module group.

These module types can be categorized according to their order penetration point in engineering and manufacturing dimensions as presented earlier in literature review part of this study. There are no direct definitions for module type's regarding their order penetration point and the categorization is done by researcher based on indirect information accumulated during this study. Definitions were verified with company's steering group of this study. Each module type is presented below in figure 16 according to its proposed engineering and production dimension.

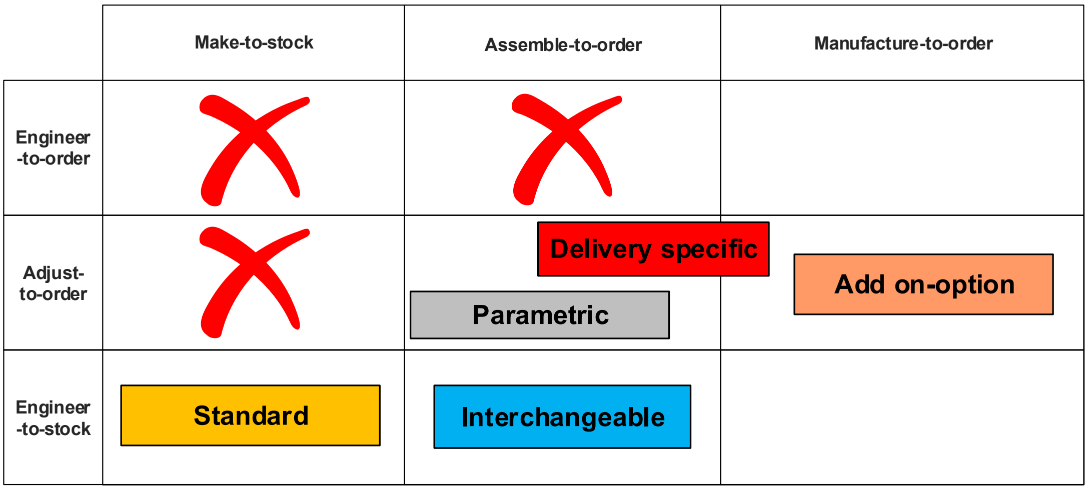

Figure 16: *Module type and order penetration point in engineering and production dimension, adaptation from figure 8*

Standard module belongs to Engineering-to-stock category as standard modules are fully designed in the product development phase well before they are linked to customer order. Production dimensions on standard modules is not exact, as depending on the relative demand volatility of the module, it can be made-to-stock or even manufactured-to-order. As make-to-stock is lead time-wise most beneficial production order penetration point and aim of this study is to investigate factory lead time reduction, we assume that standard modules in the critical path of the project are made-to-stock. Thus, standard modules order penetration point is [ETS_{ED}, MTS_{PD}].

Interchangeable modules are also fully designed in the product development phase, and thus belong and Engineering-to-stock category. As in standard modules, interchangeable modules order penetration point on production dimension can be anything from make-to-stock to manufacture-to-order. In this case, it is assumed that the relative demand volatility of interchangeable modules is in the level that allows producing module subassemblies to stock which can then be assembled-to-order. Making fully assembled interchangeable modules to stock is unfeasible, as risk of inventory obsolescence grows too large for assumed relative demand volatility. Thus, interchangeable modules order penetration point is [ETS_{ED}, ATO_{PD}].

Parametric modules are almost fully designed on product development phase but some part of the module is configurable, or parametric so that for example length of some part of the module is designed after customer order. This places parametric modules to adjust-to-order engineering dimension. We assume that parametric modules are designed so that they can be pre-fabricated to stock before customer order and assembled with final specification after customer order. Parametric modules belong to assemble-to-order production dimension. Thus, parametric modules order penetration point is [ATO_{ED}, ATO_{PD}].

Add-on options are placeholder modules for customer specific options. These modules are predesigned in product development phase, but the final design is done according to customer specifications after customer order. This places add on-option modules to adjust-to-order engineering dimension. Because add on-options are not high-volume modules and used to fulfill special customer needs, these modules have high relative demand volatility and should be placed to manufacture-to-order production dimension. Thus, add on-options order penetration point is [ATO_{ED}, MTO_{PD}].

Delivery specific modules are modules that need delivery specific design. Part of these modules is predesigned in product development phase, but varying amount of design work need to be done after customer order for each module. Because of this, delivery specific modules lie somewhere between adjust-to-order and engineer-to-order engineering dimensions, needing more design work than parametric modules, but not being fully engineer-to-order modules neither. Delivery specific modules in the critical path of the project schedule are assumed to be sub-assembled to stock and assembled fully after receiving the customer order. Thus, delivery specific modules order penetration point is [ATO_{ED}, ATO_{PD}].

Below in figure 17, module type and corresponding order penetration point delivery process is visualized as defined earlier in literature review part of this study.

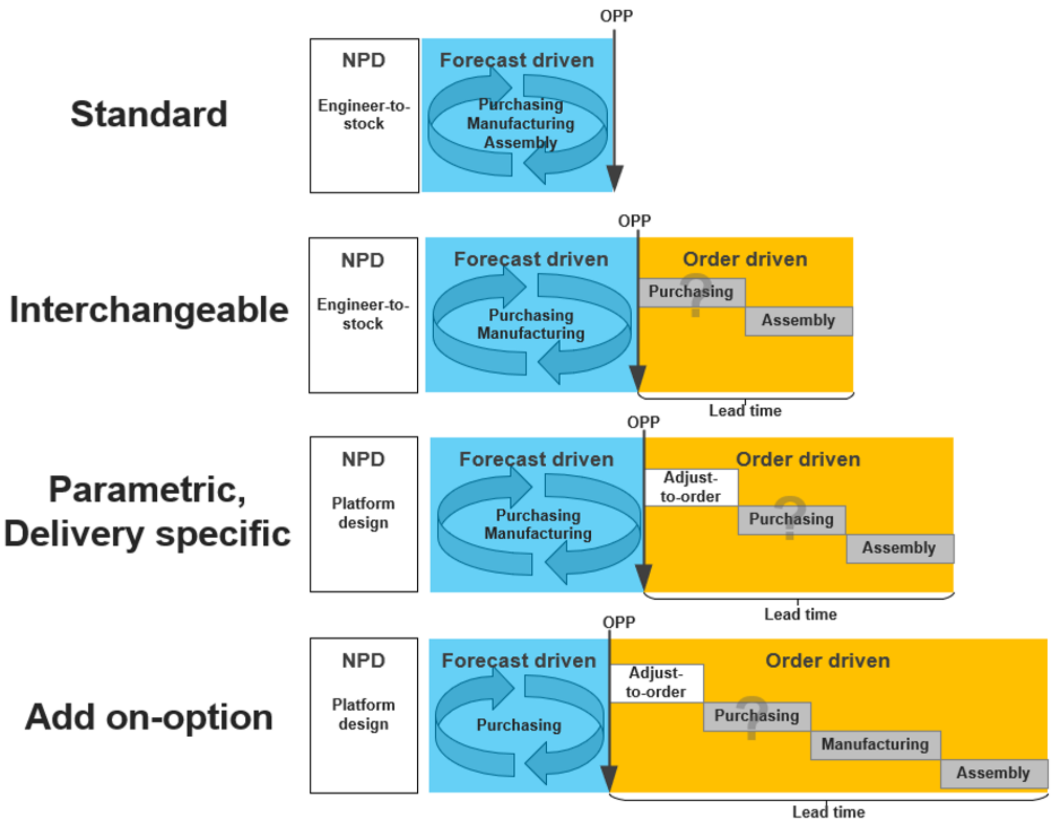

Figure 17: *Module types and delivery processes*

Modularization project and the module map covers broader range of functionality than the current ML system's scope used for this study's lead time estimation. Modular system scope has been chosen so that its functionality closely represents the system investigated in chapter 3. The chosen system scope is presented in table 6 below.

Table 6: *Modular system configuration for lead time simulation*

System group	System components
Transfer & Storage	Crane, Aisle and Load Handler
Loading Cell	Conveyor, User interface, Pallet stations, Electrics and Operator safety
Electrical interfaces	Electrical interfaces

4.2 Company vision of modularization's impact

In this chapter, the expected impact of modularization to factory phase of delivery process is presented. This company vision is compiled from the interviews conducted during the study, enriched with the discussions with the company steering group of this study.

Design department's workload per delivery project is expected to be reduced. Not all the modules have to be handled the design department during delivery process, and only some modules need actual engineering work. As the design work directly used for delivery process decreases, notable amount of design hours need to be used to keep the modules up to date regardless of the amount they are used in customer projects. Reduced workload in design department should reduce lead time from the design phase of the delivery process.

Purchasing is impacted by the modular product design by reducing calendar time needed for purchases. Purchasing time is determined by delivery project's item that has the longest lead time from supplier. Items with long lead times can be standardized so that suppliers are able to keep them in stock or make half-finished products to stock. After the order, supplier will finish the product according to order specifications and deliver it to Fastems. This has the possibility to lead to purchasing phase's lead time reduction.

Modularity can have impact in assembly lead time. Modularity enables making more frequently used modules to stock. This also increase flexibility, as at times of low assembly workload, capacity can still be used to assemble stock modules and at times of high workload, these stocked modules can be used for new delivery projects.

4.3 Methodology for lead time simulation

4.3.1 Overview

Modularization project is still in progress at Fastems so there is no actualized data available for modular system deliveries. To overcome this a methodology is created for lead time simulation purposes. Purpose of this methodology is first to simulate the lead time of modular project delivery and second to be able to compare and analyze the difference to simulated lead time of non-modular system lead time presented in chapter 3.

This study is concerned about the impact of modularity to delivery lead time and thus the methodology is created with emphasis on Ceteris paribus principle. The goal of this is to eliminate the lead time impact caused by the byproducts of modularization project that are not directly caused by modularization itself, for example higher quality of design leading to decreased assembly workload with new system. As the separation between what is directly caused by modularization and what is byproduct of the project, is unambiguous, the methodology created is explained and discussed in detail for better transparency and credibility of this study.

The preconditions, or the context to which this methodology is created is presented earlier in chapter "Modular system structure – what is defined". Gantt chart is used for lead time simulation and suitable Gantt chart tasks' level of detail is presented in chapter "Simulation tool". Then assumptions about the delivery process of modular structure, delivery process properties of module types and similarities to non-modular system are defined. After this the lead time calculation rules for Gantt tasks are deduced using the preconditions and assumptions defined earlier. It is acknowledged that the defined assumptions and calculation rules cause uncertainty to study's results and thus scenario analysis is used to form calculation rules for two scenarios. These scenarios are then simulated, and delivery lead time defined for both scenarios. By analyzing these two scenarios, estimation about the sensitivity of results to calculation rule parameters can be done and by comparing the lead time simulations of modular system to original system lead time simulation, the difference is analyzed in chapter 5.

4.3.2 Assumptions

This chapter includes the assumptions concerning the methodology used for lead time simulation. These assumptions were created based on the already defined things about modularity at the case company, the company vision of modularity and the insight gained during the literature review.

Lead time calculation starts from the beginning of pre-design phase same way as in the current lead time estimation process and lead time of three weeks is used. As pre-design consists mostly from load handling, layout and lead design activities and partly overlap with sales phase of delivery. Due to pre-design dependency to sales process and by that to customer interface and connections to modularity are unclear, the pre-design phase is treated the same way as in current lead time estimation and no closer analysis of pre-design phase is performed.

System component specific processes start after pre-design phase. For each system component, Gantt chart simulating the system component's lead time is created. As system component's delivery process is analyzed on module type level as seen in figure 18, module type assumptions are considered when simulating the delivery process.

Assumptions concerning module types defined in table 7. These assumptions used for different module types are then mapped in table 8.

Table 7: *Module type assumptions and definitions*

	Assumption	Explanation
Design	**No design time**	Modules are always standard or chosen from already designed alternatives and no design is needed.
	Short design time	Design is needed only to derive the module to customer need by changing pre-defined parameters of the module. Design time for module type group is 1 day.
	Delivery specific design	Design effort required for delivery specific design is minimized by creating clever design solutions when designing the modular system structure and impact of customer specific needs for design is confined to chosen modules. One week design lead time is used for module type's group.
Purchasing	**Stocking of materials**	Demand for modules is high enough to justify stocking of all the needed materials. This eliminates purchasing time during delivery project.
	Short purchasing lead time for parametric components	Structure of the module is designed so that the components which are affected by the pre-defined parameters reliant on customer needs, have short lead time.
	Decoupling of long lead time components and customer need	Product structure is designed so that long lead time components are not affected by the parameters defined by customer need.
Assembly	**Assemble to stock**	Module assembly can be made to stock and module assembly lead time is eliminated during the delivery project.
	Demand	There is limited amount of interchangeable modules to ensure there is enough demand for every module and that way assembling to stock is sensible.
	Semi-finished goods	Module structure is mostly standardized, but there is a part which's dimensions or quantity can change according to customer need. Subassemblies of module can be made to stock and after customer order the part that derives the module according to customer need can be manufactured and module can then be assembled. This reduces the lead time of the module as large parts of it can be made to stock.

Table 8: *Module type assumption mapping*

	Assumptions	Standard	Interchangeable	Parametric	Delivery specific
Design	No design time				
	Short design time				
	Delivery specific design				
Purchasing	Stocking of materials				
	Short purchasing lead time for parametric components				
	Decoupling of long lead time components and customer need				
Assembly	Assemble to stock				
	Demand				
	Semi-finished goods				

Assumptions about add on -option modules are left out, as the defined system scope in question does not include any optional features and thus do not concern this study.

With assumptions defined above, default design and purchasing lead times for different module type groups are specified. Assembly lead time definition requires more assumptions to be made about the delivery process.

The combined assembly and test workload between system component and equivalent non-modular subsystem is assumed to be equal. This assumption is done as there is no information available about assembly workload for the modular system and so caution is used.

Default assembly process is defined as follows. Module type group's assembly is started after materials are available. During this phase modules are assembled as close to completion as possible. Modules that are made to stock can be taken from stock and semi-finished module assemblies are finished after needed materials arrive. After all the system component's module type groups have been assembled, system component's final assembly begins. During this phase modules and subassemblies are joined together to form the completed system level component. After system level component's final assembly phase, possible testing phase is started. Example of this process is given in the figure 18. This default process can be expanded by module type assumptions.

System components and corresponding non-modular system subassembly mapping is presented in table 9. Also, module types and quantities are presented for system components. As modular and non-modular systems have different mechanical structures and conceptual partitions about the system parts, the mapping between modular and non-modular system parts is not ambiguous. Regardless of this imperfection, the mapping below gives us a frame to work with.

Table 9: *Non-modular subsystem - system component mapping and corresponding module quantities*

Non-modular Subsystem System component	Standard	Interchangeable	Parametric	Delivery specific	Total
Aisle	**5**		**9**		**14**
Aisle	5		9		14
DMC	**26**	**17**	**6**		**49**
Crane	22	13	5		40
Load Handler	4	4	1		9
Electric	**7**	**6**	**2**	**1**	**16**
Electrics		1			1
Electrical interfaces	7				7
User interface		4			4
Operator safety		1	2	1	4
LSM		**15**	**1**	**2**	**18**
Pallet stations		15	1	2	18
Material station		**2**			**2**
Conveyor		2			2

Non-modular subsystems from chapter three are presented in bolded and highlighted rows. Modular structure's system components forming approximately equal entity are presented below the non-modular subsystem rows. For every system component row, quantity of each module type is presented. Module type quantities are summed together on the corresponding non-modular subsystem row to get the number of modules that is needed to compose similar structure with non-modular subsystem.

As stated before, it is assumed that assembly workloads for subsystems and corresponding system component combinations are equal. It is also assumed that workload completion velocity per assembly process is constant between each non-modular subsystem and corresponding modular system component. Assuming that each module in the system component requires roughly equal amount of work to be assembled, assembly workload per system component can be allocated to individual modules. Even though this simplification can distort single module's assembly workload with significant amount, the final lead time is examined on aggregate level consisting of 99 modules and thus individual distortion's effect to end result is assumed to be marginal.

With assumptions above, average assembly lead time for one module in each system component can be calculated by dividing the total quantity of modules needed for equivalent non-modular subsystem with the total assembly lead time of that non-modular system component. The validity of this operation lies in assumption that in the non-modular system, assembly work was done in a series of assembly works forming one timeline of assembly work as with modular system structure, much of the assembly work can done in parallel.

Assuming that system assembly will be operationally divided to different system components and system component subassemblies divided to different module type subassemblies, assembly lead time of system component's module type group can be calculated by multiplying the quantity of modules in the group by average assembly lead time for one module for that system component.

4.3.3 Simulation framework and delivery process description

Gantt chart is used for lead time simulation and it is created in Microsoft Project Professional 2016 software. Simulation emphasis is on the system component level. For purpose of this research the lead time will be analyzed by grouping different module types together and then analyzing each groups delivery process and how they come together in the end to one subsystem. This enables taking advantage of different possible delivery processes of each module group and thus enables detailed level lead time analysis. Base for these delivery processes can be seen in the figure 17 "Module types and delivery processes" presented earlier. Example of system component lead time analysis Gantt chart is presented below in figure 18.

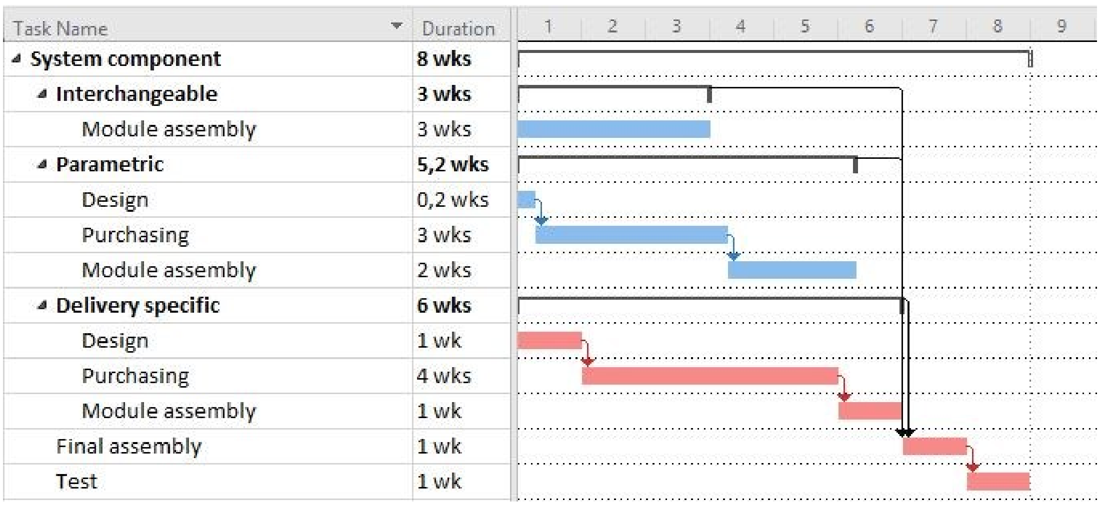

Figure 18: *Example of lead time analysis Gantt chart*

Standard modules are not shown in the lead time analysis, as all standard modules are assembled to stock. Stocked standard modules are picked from inventory and used in final assembly phase.

During delivery project semi-finished interchangeable module assemblies are completed using stock components. After interchangeable module assembly is completed, the modules are moved to wait for final assembly phase to begin.

Parametric module structures need to be derived to customer order in design phase. After short design phase, purchasing for parametric module components start. On material delivery, semi-finished modules' base assemblies are completed, and parametric modules are moved to wait for final assembly phase to begin.

Delivery specific module components are designed at the start of system component process. After design phase, delivery specific module components can be purchased and on material delivery semi-finished modules' base assemblies are completed and modules are moved to wait for final assembly phase to begin.

When all module assemblies are completed, system components final assembly phase can begin. Final assembly phase assemblies all the system component module's together and if system component requires testing phase, it can be started after the final assembly phase is completed.

Modular system components lead time simulation will be visualized in groups presented below in table 10.

Table 10: *System component lead time visualization groups in Gantt chart*

System group	System component	Gantt group
Electrical interfaces	Electrical interfaces	-
Loading Cell	Conveyor	Loading cell
	Operator safety	Loading cell
	Pallet station	Loading cell
	Electrics	-
	User interface	-
Transfer & Storage	Aisle	Aisle
	Crane	Double mast crane
	Load Handler	Double mast crane

System components electrical interfaces, electrics and user interface are not visible in the Gantt charts. These system components include only standard and interchangeable modules and thus they have no design or purchasing phase. These system components situated in the Electrics subsystem of non-modular system. Electrics subsystem included only design and purchasing process in non-modular system and the assembly work for Electrics was performed during other subsystem assemblies. Because of this the actual workload of Electrics assembly is already allocated indirectly to other modular system components and thus no assembly work for these system components is not visible in Gantt charts.

Loading cell system group is examined as a whole in system component lead time simulations. As conveyor is used in modular system to perform the functionality of equivalent non-modular material station and material station was procured in whole from supplier, no information about assembly lead time is available. The relatively simple structure of material station compared to crane and loading station moving justifies the assumption of maximum of 4 weeks of assembly lead time for material station assembled by Fastems as the equivalent assembly lead time for crane and loading station moving is 5 weeks.

Transfer & storage is divided in two for clarity, as Aisle has no process dependencies to other system components. Crane and Load Handler are examined together in system component lead time simulation as they have joined final assembly and testing phase.

System components chosen to lead time simulation are analyzed first separately and in the end the results from individual system component analysis are integrated to system level lead time simulation.

4.3.4 Uncertainty management – scenario analysis

This study includes particularly large amount of assumptions to which the results are based. To tackle the uncertainty that these assumptions cause thus diluting the credibility of results, scenario analysis is carried out. With the scenario analysis, it is possible to evaluate the sensitivity of the results to chosen simulation parameters.

Simple scenario analysis is carried out by creating two parameter sets for two scenarios. Scenario 1, the base scenario, resembles the situation where modular system creation goes as planned and benefits of well-planned product structure can be realized. Scenario 2, the risk scenario, imitates the situation where all the benefits of modular system can't be realized in the full scope expected by Fastems.

Scenario analysis does not affect the design process of the modular system and given assumption about design lead times are not varied for different scenarios. This approach is chosen as probability of deviation in purchasing and assembly lead times is believed to be considerably higher.

Purchasing lead time for parametric modules is affected by scenario analysis. The lead time in base scenario is 3 weeks and in risk scenario 5 weeks. The assumption "Short purchasing lead time for parametric components" in table 1337 assumes that all the parametric modules and the parametric components can be designed so that they have short purchasing lead time, essentially meaning that they can be manufactured quickly. This question boils down to if all the parametric components can be designed to require only limited amount of manufacturing technologies per component and if the technologies involved allow for short manufacturing lead time.

Purchasing lead time for delivery specific modules is also affected in the scenario analysis. The base scenario is assumed to have a lead time of 4 weeks and risk scenario lead time of 6 weeks. The assumption “Decoupling of long lead time components and customer need” assumes that delivery specific design should not be included to any component that has long lead time and thus maximum purchasing lead time of 4 weeks can be assumed in base scenario. Being able to design mechanical structure that enables this is not given, and thus maximum purchasing lead time of 6 weeks is used in risk scenario.

Assembly lead time is affected in three ways by scenario analysis. First deviation concerns the assumption “Semi-finished goods” which dictates that part of the interchangeable, parametric and delivery specific module’s assembly work can be done before all the materials have arrived, because standard components that are already available, can be assembled together beforehand.

The base scenario assumption for percentage of assembly work that can be done beforehand is 70% for interchangeable modules and 30% for parametric and delivery specific modules. The risk scenario assumes that 50% of total assembly work for interchangeable modules and 0% assembly work for parametric and delivery specific modules can be done before the rest of the materials have arrived.

The second way in which assembly phase is affected by scenario analysis is by allocation of total workload to module assembly versus system component’s final assembly. In base scenario it is assumed that 80% of total assembly workload can be done already in the module assembly phase and final assembly phase takes 20% of the total system component’s assembly workload. In risk scenario this ratio is assumed to be 60% of workload in module assembly phase and 40% of workload in final assembly phase. This ratio will be dependable on the success of modular product design, as most of the well-designed module’s assembly work should be possible to be done in the module assembly phase before the final assembly.

4.3.5 Lead time calculation rules

In this chapter the methodology presented is condensed to a set of lead time calculation rules. Lead time calculation rules for base and risk scenarios are presented in table 11 below. Obviously, lead time calculation rules do not consider forecast driven activities, as they should be carried out separately from delivery project and thus don't impact the lead time of the system.

Table 11: *Lead time calculation rules for base and risk scenario*

Base scenario	Standard	Interchangeable	Parametric	Delivery specific
Design	none	none	1 day	1 week
Purchasing	none	none	3 weeks	4 weeks
Module assembly	none	$\frac{t_{total}}{Q_{total}} * Q_{module\ type} * 0{,}24$	$\frac{t_{total}}{Q_{total}} * Q_{module\ type} * 0{,}56$	
Final assembly	$\frac{t_{total}}{Q_{total}} * Q_{system\ component} * 0{,}2$			
Risk scenario	**Standard**	**Interchangeable**	**Parametric**	**Delivery specific**
Design	none	none	1 day	1 week
Purchasing	none	none	5 weeks	6 weeks
Module assembly	none	$\frac{t_{total}}{Q_{total}} * Q_{module\ type} * 0{,}3$	$\frac{t_{total}}{Q_{total}} * Q_{module\ type} * 0{,}6$	
Final assembly	$\frac{t_{total}}{Q_{total}} * Q_{system\ component} * 0{,}4$			

$$t_{total} = Assembly\ lead\ time\ of\ comparison\ non-modular\ subsystem$$
$$Q_{total} = Module\ quantity\ required\ for\ comparison\ non-modular\ subsystem$$
$$Q_{module\ type} = Module\ quantity\ in\ system\ component's\ module\ type\ group$$
$$Q_{system\ component} = Total\ module\ quantity\ of\ system\ component$$

In both scenarios standard and interchangeable modules are made-to-stock and thus they can be taken straight to final assembly phase from inventory. Design process lead time is the same in both scenarios for parametric modules and delivery specific modules. In base scenario, purchasing phase for parametric modules needs 3 weeks lead time and for delivery specific modules 4 weeks. In risk scenario, purchasing lead time of 5 weeks for parametric modules is used and 6 weeks for delivery specific modules.

Visualization of when assembly work is done during project in base scenario can be seen in figures 19 and 20 below. Module assembly lead time for interchangeable, parametric and delivery specific modules in base scenario is calculated by first calculating the total assembly lead time for module group, including final assembly, with equation $\frac{t_{total}}{Q_{total}} * Q_{module\ type}$. In base scenario 80% of total assembly work can be done in module subassembly phase and 20% in final assembly phase, as seen if figures 19 and 20. As part of the subassembly work can be forecast driven according to “Semi-finished goods” assumption, the total order driven subassembly work is 30% for interchangeable module group’s subassembly work. As subassembly work is 80% of interchangeable module group’s total assembly work and 30% if this work is order driven, 24% of interchangeable module group’s total subassembly work is order driven and 56% forecast driven.

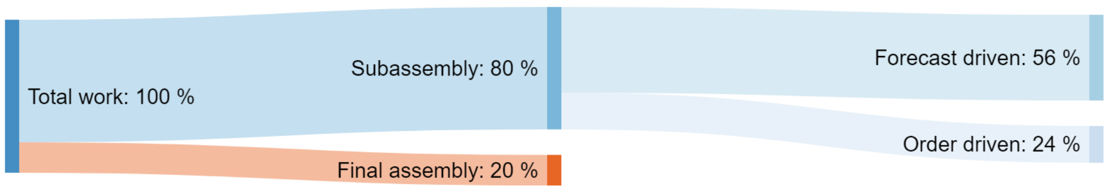

Figure 19: *Assembly work, interchangeable module groups, base scenario*

For parametric and delivery specific modules in base scenario, only 30% of subassembly work can be order driven and 70% of subassembly workload is order driven. This leads to 56% of total work being order driven subassembly work and 24% being forecast driven subassembly work, as seen in figure 20 below.

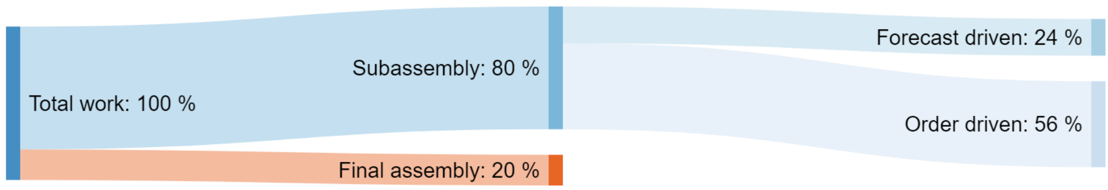

Figure 20: *Assembly work, parametric and delivery specific module groups, base scenario*

The calculation rationale is the same in risk scenario as in base scenario, with two changes. The workload allocation between module assembly and final assembly is less favorable in risk scenario,and only 60% of the workload can be done in the module assembly phase and 40% in the final assembly phase. Also, forecast driven subassembly work ratio for interchangeable modules is dropped from 70% to 50%, meaning that less work can be done according to forecast and more work need to be done during the delivery project. Below in figure 21 impact of these changes is visualized for interchangeable module groups assembly work in risk scenario.

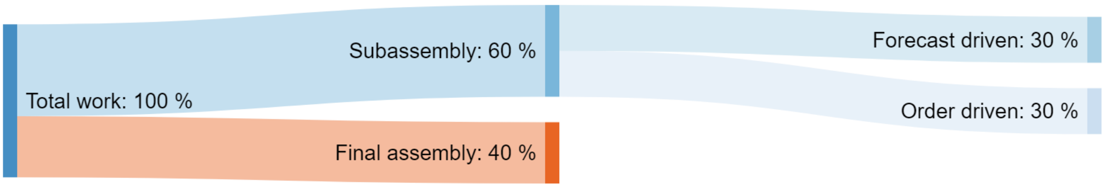

Figure 21: *Assembly work, interchangeable module groups, risk scenario*

In risk scenario, concerning the parametric and delivery specific modules, “Semi-finished goods: parametric and delivery specific modules” assumption is waived. All the assembly work for parametric and delivery specific modules is order driven and completed during delivery project. Thus 60% of total work is order driven subassembly work and 40% is final assembly work for parametric and delivery specific module groups in risk scenario, which is visualized in figure 22.

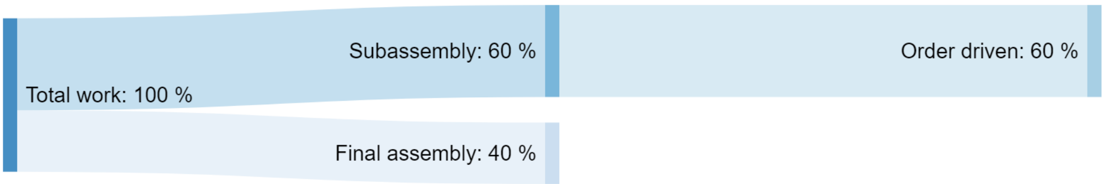

Figure 22: *Assembly work, parametric and delivery specific module groups, risk scenario*

As the final assembly work ratio is constant across different module groups, the relative size of module group compared to others in the same system component does not matter when calculating the final assembly work. Thus, system components final assembly work can be calculated by calculating the total system component’s total assembly time and multiplying it with parameter defining the workload ratio between subassembly and final assembly phases. The final assembly ratio parameter for base scenario is 20% and for risk scenario 40%. For instance, below in figure 23, system component’s assembly work composition is visualized in base scenario where system components consist equal parts of different module types, e.g. different module groups have identical quantity of modules.

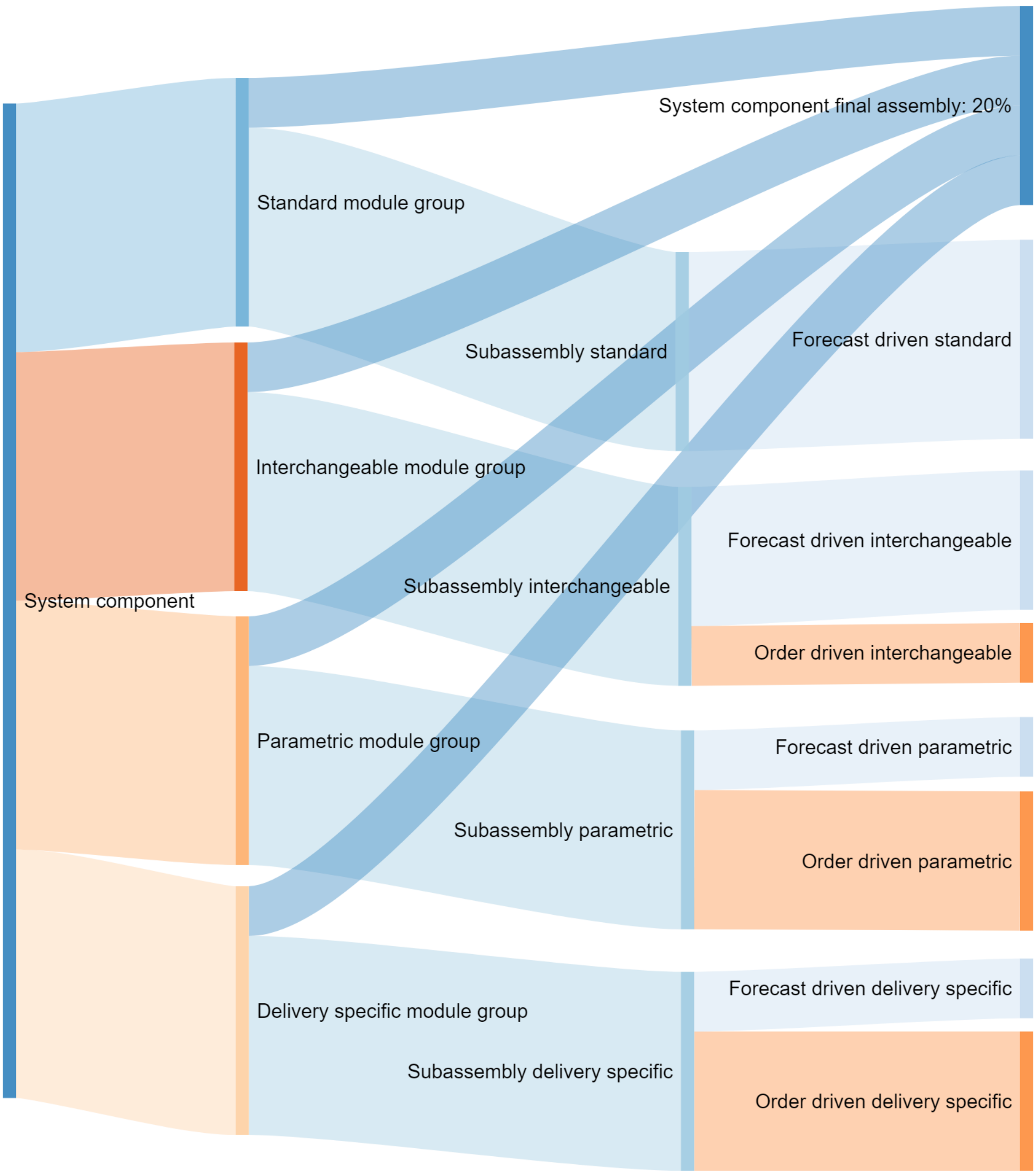

Figure 23: *Example of system component's assembly work composition in base scenario*

System component's total assembly time is $\frac{t_{total}}{Q_{total}} * Q_{system\ component}$. Here term $\frac{t_{total}}{Q_{total}}$ represent the average assembly work lead time for one module off all the modules that are needed to build the functionality of comparison non-modular subsystem. $Q_{system\ component}$ is the number of modules used to assemble system component that fulfills part, or fully, functional requirements of comparison non-modular subsystem. This is possible to do, as it is assumed that fulfilling the same functionality requirements in modular and non-modular systems, requires equal amount of assembly work.

4.4 Modular system lead time simulation

Microsoft excel was used to code lead time calculation rules and calculate the lead time for every delivery process part in this study's system scope. These lead times were then imported to Microsoft Project to create Gantt charts with process dependencies defined earlier. First, lead time for individual system components in different scenarios is presented. In the end of this chapter the lead time for whole system in different scenarios is presented in Gantt charts.

Lead times of modular Aisle system component is presented below. In figure 24, the base scenario for lead time is presented and in figure 25 the lead time if risk scenario realizes is presented.

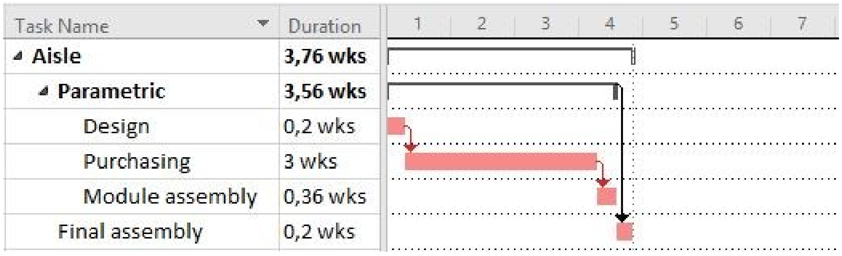

Figure 24: *Modular Aisle lead time in base scenario*

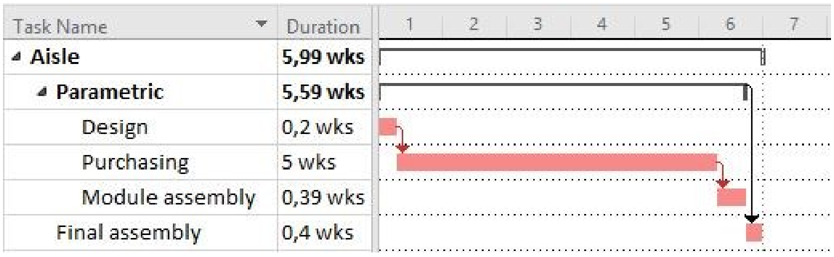

Figure 25: *Modular Aisle lead time in risk scenario*

Lead time for modular aisle in base scenario is 3,76 weeks and 5,99 weeks in risk scenario.

Lead time formation of modular Double mast crane in base scenario is presented in figure 26 and in risk scenario in figure 27. Double mast crane consists of system components Crane and Load handler, which are assembled together in the final assembly phase and tested.

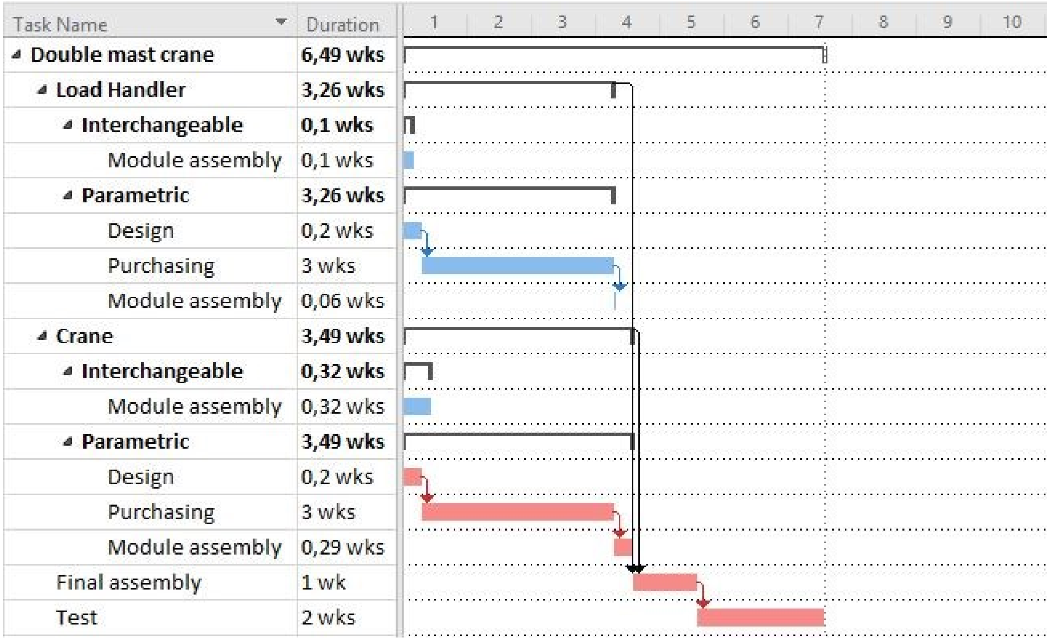

Figure 26: *Modular Double Mast Crane lead time in base scenario*

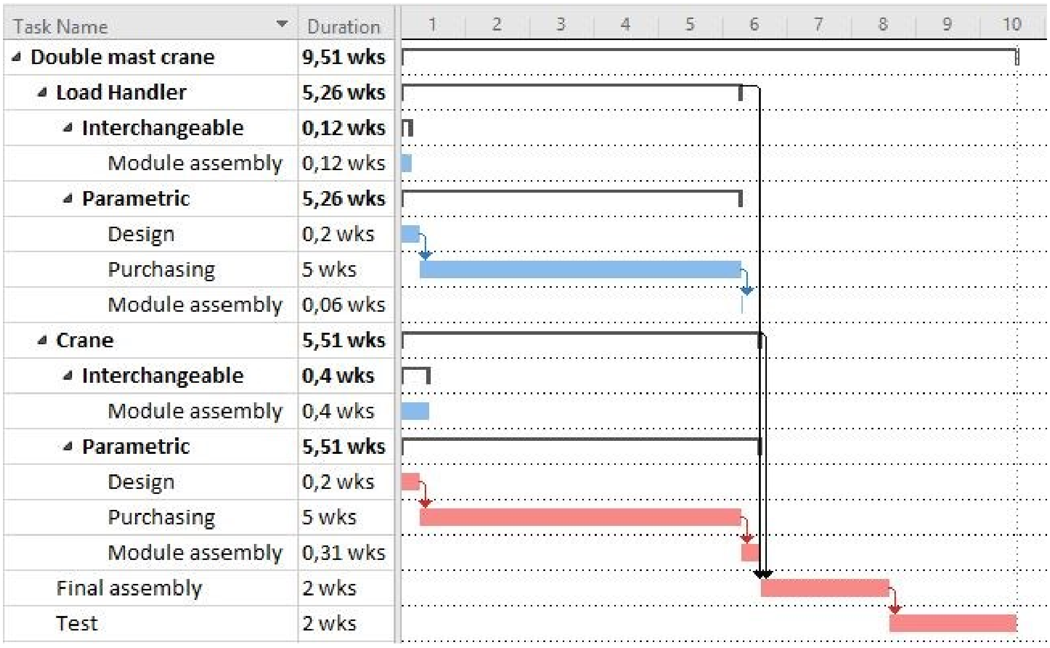

Figure 27: *Modular Double Mast Crane lead time in risk scenario*

Lead time for modular Double mast crane in base scenario is 6,49 weeks and in risk scenario 9,51 weeks. System component Crane and Load handler have close to equal lead times and concerning the precision of this lead time simulation they can be thought as equal.

Lead time formation of Loading Cell system group and its system components in base scenario is presented in figure 28 and in risk scenario in figure 29.

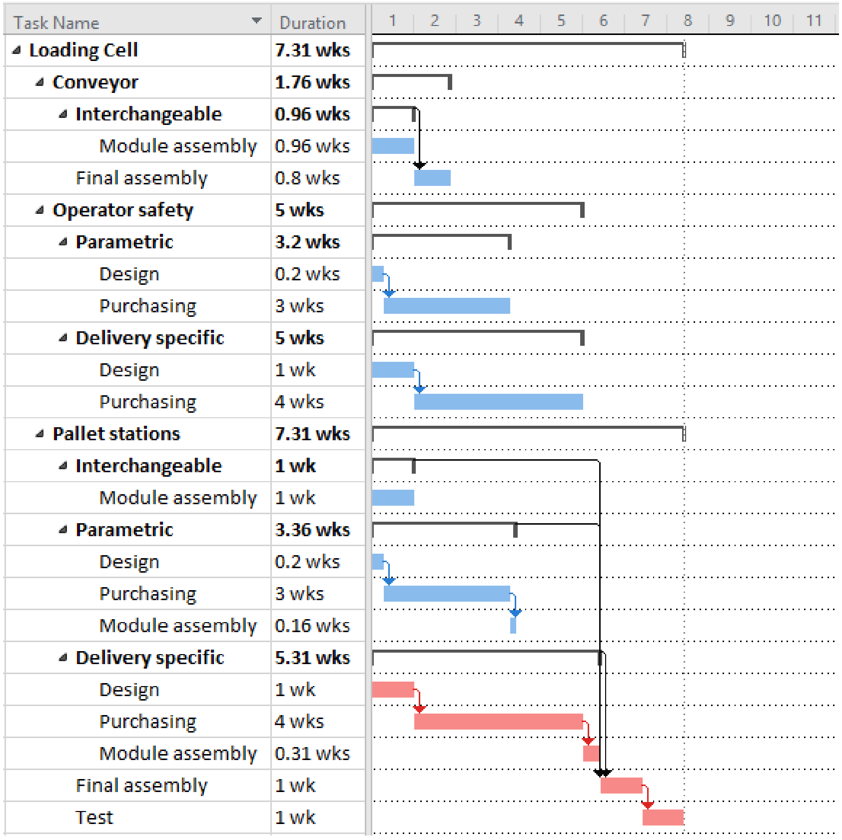

Figure 28: *Modular Loading Cell lead time in base scenario*

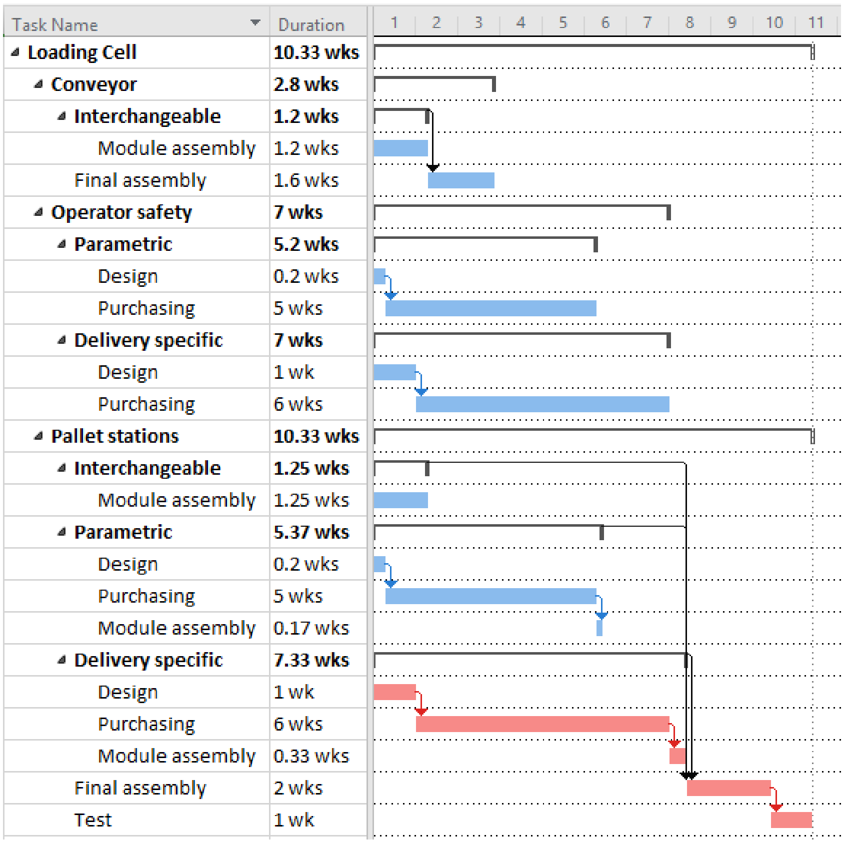

Figure 29: *Modular Loading Cell lead time in risk scenario*

Lead time of loading cell system group in base scenario is 7,31 weeks and in risk scenario 10,33 weeks.

Even though assembly time for non-modular material station was estimated to 4 weeks and this was used as a basis for workload allocation for modular conveyor, conveyor's total lead time in modular system is only 1,76 weeks in base scenario and 2,8 weeks in risk scenario.

Operator safety lead time is 5 weeks in base scenario and 7 weeks in risk scenario. The difference between scenarios is caused directly by delivery specific purchasing lead time assumption. As the actual purchasing lead times can have high variance depending on the purchased materials, caution should be used if conclusions are drawn from operator safety lead time simulation.

Pallet stations lead time is 7,31 weeks in base scenario and 10,33 weeks in risk scenario and it is clearly on the critical path of Loading Cell system group delivery process.

Total factory lead time for modular system in base scenario is presented in figure 30 and for risk scenario in figure 31.

Task Name	Duration
Base scenario	**10.31 wks**
Pre-design	3 wks
System components	**7.31 wks**
Aisle	**3.76 wks**
Parametric	**3.56 wks**
Design	0.2 wks
Purchasing	3 wks
Module assembly	0.36 wks
Final assembly	0.2 wks
Double mast crane	**6.49 wks**
Load Handler	**3.26 wks**
Interchangeable	**0.1 wks**
Module assembly	0.1 wks
Parametric	**3.26 wks**
Design	0.2 wks
Purchasing	3 wks
Module assembly	0.06 wks
Crane	**3.49 wks**
Interchangeable	**0.32 wks**
Module assembly	0.32 wks
Parametric	**3.49 wks**
Design	0.2 wks
Purchasing	3 wks
Module assembly	0.29 wks
Final assembly	1 wk
Test	2 wks
Loading Cell	**7.31 wks**
Conveyor	**1.76 wks**
Interchangeable	**0.96 wks**
Module assembly	0.96 wks
Final assembly	0.8 wks
Operator safety	**5 wks**
Parametric	**3.2 wks**
Design	0.2 wks
Purchasing	3 wks
Delivery specific	**5 wks**
Design	1 wk
Purchasing	4 wks
Pallet stations	**7.31 wks**
Interchangeable	**1 wk**
Module assembly	1 wk
Parametric	**3.36 wks**
Design	0.2 wks
Purchasing	3 wks
Module assembly	0.16 wks
Delivery specific	**5.31 wks**
Design	1 wk
Purchasing	4 wks
Module assembly	0.31 wks
Final assembly	1 wk
Test	1 wk

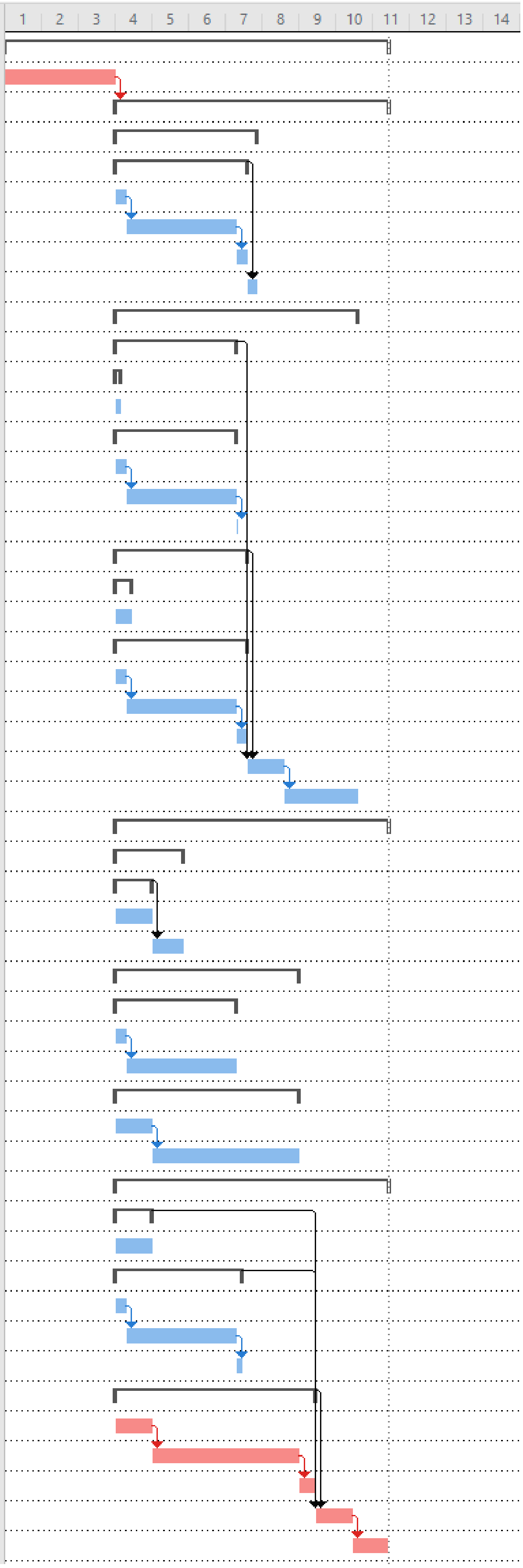

Figure 30: *Modular system lead time in base scenario*

Task Name	Duration
Risk scenario	**13.33 wks**
Pre-design	3 wks
System components	**10.33 wks**
Aisle	**5.99 wks**
Parametric	**5.59 wks**
Design	0.2 wks
Purchasing	5 wks
Module assembly	0.39 wks
Final assembly	0.4 wks
Double mast crane	**9.51 wks**
Load Handler	**5.26 wks**
Interchangeable	**0.12 wks**
Module assembly	0.12 wks
Parametric	**5.26 wks**
Design	0.2 wks
Purchasing	5 wks
Module assembly	0.06 wks
Crane	**5.51 wks**
Interchangeable	**0.4 wks**
Module assembly	0.4 wks
Parametric	**5.51 wks**
Design	0.2 wks
Purchasing	5 wks
Module assembly	0.31 wks
Final assembly	2 wks
Test	2 wks
Loading Cell	**10.33 wks**
Conveyor	**2.8 wks**
Interchangeable	**1.2 wks**
Module assembly	1.2 wks
Final assembly	1.6 wks
Operator safety	**7 wks**
Parametric	**5.2 wks**
Design	0.2 wks
Purchasing	5 wks
Delivery specific	**7 wks**
Design	1 wk
Purchasing	6 wks
Pallet stations	**10.33 wks**
Interchangeable	**1.25 wks**
Module assembly	1.25 wks
Parametric	**5.37 wks**
Design	0.2 wks
Purchasing	5 wks
Module assembly	0.17 wks
Delivery specific	**7.33 wks**
Design	1 wk
Purchasing	6 wks
Module assembly	0.33 wks
Final assembly	2 wks
Test	1 wk

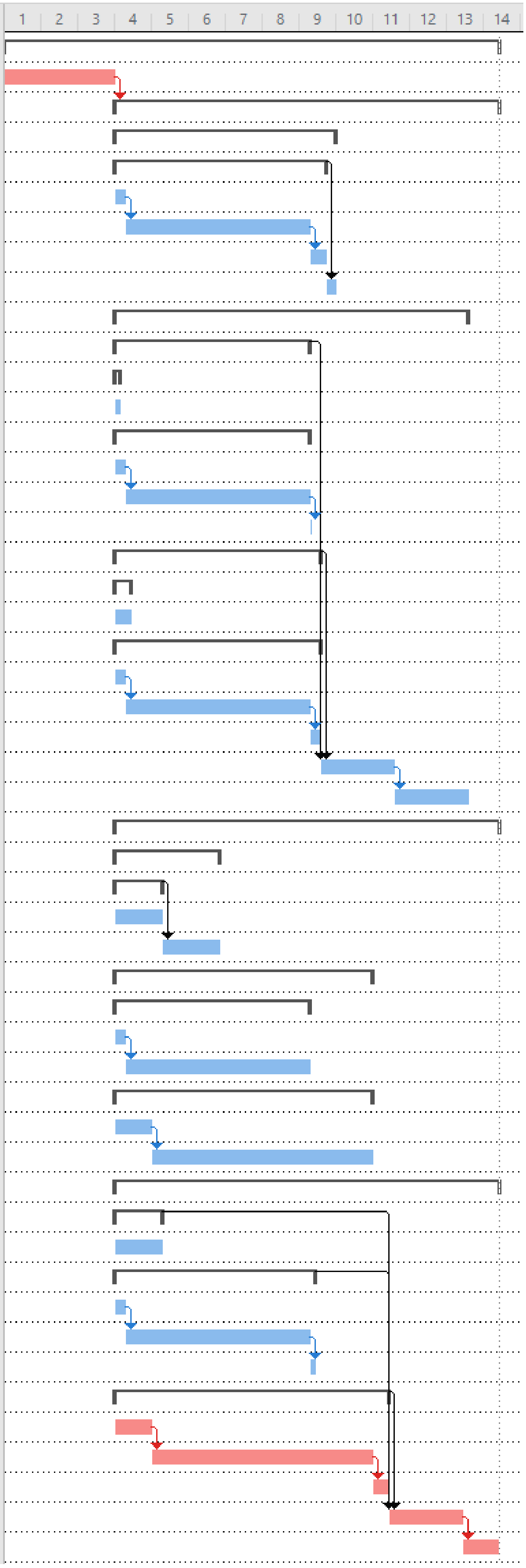

Figure 31: *Modular system lead time in risk scenario*

Modular system lead time in base scenario is 10,31 weeks and in risk scenario 13,33 weeks. Process starts with 3 weeks of pre-design phase, after which system component specific processes begin. In both scenarios, pallet station’s delivery specific modules are on the critical path of the project delivery phase. Double mast crane is also close to pallet stations lead time in both scenarios and thus in a risk of being on critical path of the project delivery.

5. DISMANTLING THE LEAD TIME IMPACT OF MODULARITY

In this chapter, the lead time difference between non-modular and different modular scenarios is analyzed. Analysis on done on the basis of original, non-modular structure, and because of that system is studied as it was in the modular system Gantt charts, but as it was presented in the non-modular system Gantt chart. First broad image of lead time reduction in different project phases is presented, after which individual project phases are analyzed separately. Pre-design is not included in analysis as it was not affected.

Comparison of non-modular and modular system lead time is presented in table 12 below. Visual presentation of lead time difference is presented in figure 32 below table 12.

Table 12: *Lead time difference between non-modular and modular system*

Phase	Non-modular	Modular base scenario		Modular risk scenario	
	Lead time (w)	Lead time (w)	% diff.	Lead time (w)	% diff.
Aisle	8.0	3.8	-53%	6.0	-25%
DMC	17.0	6.5	-62%	9.5	-44%
Electric	10.0	5.0	-50%	7.0	-30%
LSM	16.4	7.3	-55%	10.3	-37%
Material station	11.2	1.8	-84%	2.8	-75%
System total	**20.0**	**10.3**	**-48%**	**13.3**	**-33%**

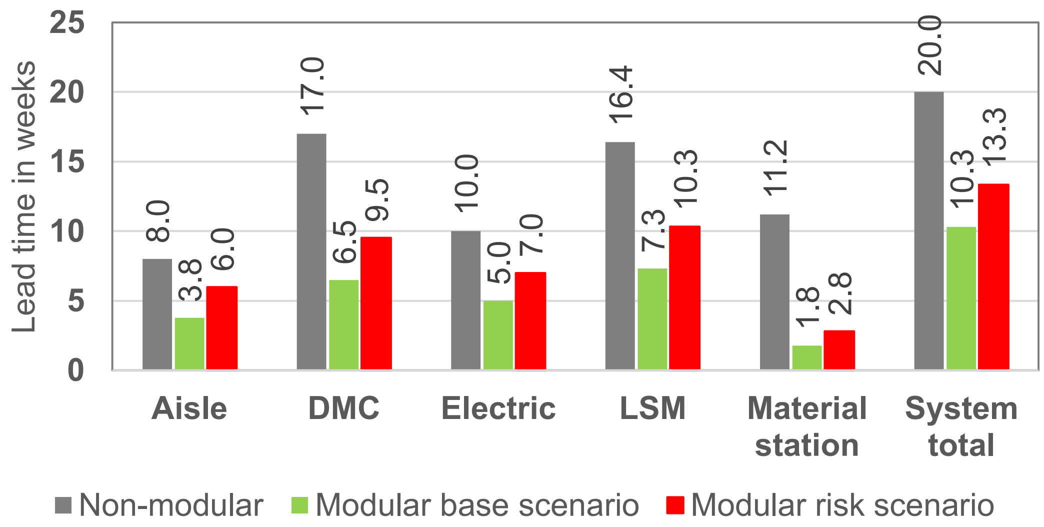

Figure 32: *Lead time difference between non-modular and modular system*

The analysis is carried out according to following logic

- Analysis is interested in the critical path of system component delivery process, especially change in the length of the critical path, i.e. the lead time difference between non-modular and modular system.
- Basic process parts are design, purchasing and assembly. Predesign and testing is part of the lead time, but no change was made to them in the simulation, so they are not analyzed either.
- Lead time change in each of these processes in the critical path of system component delivery process is calculated. Sum of these changes is the total lead time reduction for system component.
- Assembly lead time impact can be divided to two categories:
    - Lead time impact of forecast driven assembly
    - Lead time impact of parallel assembly

Analyzing the lead time impact to design and purchasing is straightforward, as impact can be calculated by deducting design or purchasing process lead time on modular system component critical path from corresponding process lead time on critical path of non-modular system. Total assembly lead time impact can be calculated the same way as design and purchasing lead time impact. To understand how much forecast driven assembly and assembly done in parallel impacts the lead time, we need to divide the total assembly lead time reduction to these two factors. Visual explanation on how this can be done is presented below in figure 33.

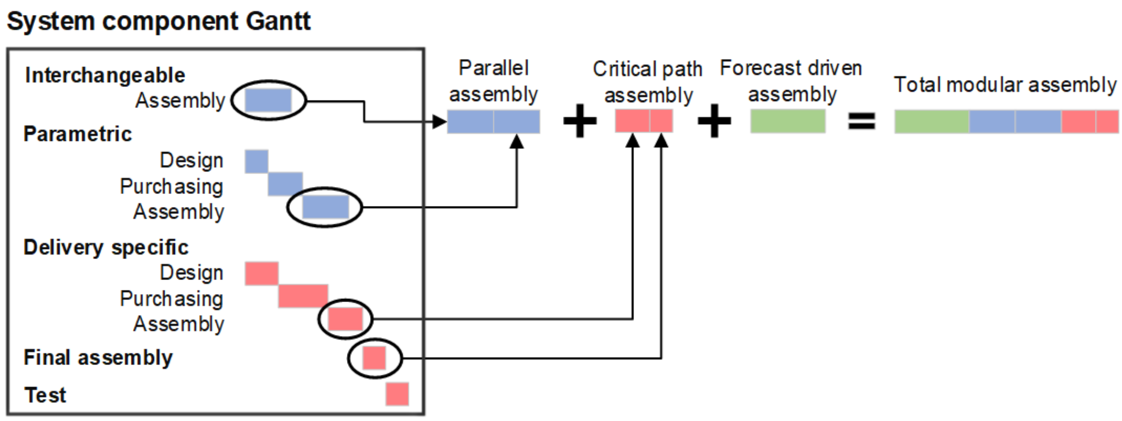

Figure 33: *Dividing assembly lead time impact to factors*

On the left side of the figure 33, example of modular system component delivery process is presented as Gantt chart. Blue bars visualize process parts not in the critical path of the delivery process and red bars represent the critical path of the delivery process. Process parts not in the critical path of the delivery process are nominated as parallel processes; these processes can be done parallel with the processes on the critical path and thus they have no effect on the lead time.

The lead time of system component consists of the process parts in the critical path of the delivery process and in the example figure above, total assembly lead time of system component consists of delivery specific assembly and system component final assembly. Total order driven assembly workload can be calculated by adding together parallel assembly processes and critical path assembly processes. Part of the assembly work for modular system component is possibly forecast driven, which is presented as green bar in the figure 33. If we add together the parallel assembly, critical path assembly and forecast driven assembly workloads, we get the total assembly workload for that system component, presented on the right side of the figure 33.

Total assembly workload for system component does not change between non-modular and modular systems, as noted in the chapter “Assumptions”, so we can use non-modular system component’s assembly workload as total assembly workload for modular system component and solve impact of parallel assembly and forecast driven assembly to system component’s lead time from the equation presented in the figure 33.

The lead time impact of modularity in each project phase and process is presented in table 13. LSM phase is highlighted because it lies in the critical path of the system delivery process.

Table 13: *Lead time impact of modularity in project phases and processes*

Lead time for design, purchasing and assembly in non-modular and modular system				
Phase	**Process**	**Non-modular**	**Modular, base scenario**	**Modular, risk scenario**
Aisle	Design	1.0	0.2	0.2
		Diff.	*-0.8*	*-0.8*
	Purchasing	6.0	3.0	5.0
		Diff.	*-3.0*	*-1.0*
	Assembly	1.0	0.6	0.8
		Diff.	*-0.4*	*-0.2*
	Total lead time	**8.0**	**3.8**	**6.0**
		Diff.	***-4.2***	***-2.0***
DMC	Design	5.0	0.2	0.2
		Diff.	*-4.8*	*-4.8*
	Purchasing	5.0	3.0	5.0
		Diff.	*-2.0*	*0.0*
	Assembly	5.0	1.3	2.3
		Diff.	*-3.7*	*-2.7*
	Total lead time	**17.0**	**6.5**	**9.5**
		Diff.	***-10.5***	***-7.5***
Electric	Design	5.0	1.0	1.0
		Diff.	*-4.0*	*-4.0*
	Purchasing	5.0	4.0	6.0
		Diff.	*-1.0*	*1.0*
	Total lead time	**10.0**	**5.0**	**7.0**
		Diff.	***-5.0***	***-3.0***
LSM	Design	3.0	1.0	1.0
		Diff.	*-2.0*	*-2.0*
	Purchasing	7.4	4.0	6.0
		Diff.	*-3.4*	*-1.4*
	Assembly	5.0	1.3	2.3
		Diff.	*-3.7*	*-2.7*
	Total lead time	**16.4**	**7.3**	**10.3**
		Diff.	***-9.1***	***-6.1***
Material station	Design	2.0	0.0	0.0
		Diff.	*-2.0*	*-2.0*
	Purchasing	9.2	0.0	0.0
		Diff.	*-9.2*	*-9.2*
	Assembly	0.0	1.8	2.8
		Diff.	*1.8*	*2.8*
	Total lead time	**11.2**	**1.8**	**2.8**
		Diff.	***-9.4***	***-8.4***

In table 14, assembly workload is broken down in each project phase to forecast driven assembly, order driven parallel assembly and order driven critical path assembly, which equals the assembly lead time of that phase. Thing worth noticing is that in non-modular system, whole workload belongs to critical path of each project phase. By moving assembly work away from critical path, we reduce the lead time of the corresponding assembly phase. LSM assembly phase is highlighted as it belongs to critical path of whole delivery process.

Table 14: *Assembly workload breakdown*

Assembly workload breakdown in modular system			
	(weeks)	Modular, base scenario	Modular, risk scenario
Aisle	**Total workload**	**1.0**	**1.0**
	Forecast driven assembly	-0.4	-0.2
	% of total assembly	*-44%*	*-21%*
	Order driven, parallel assembly	0.0	0.0
	% of total assembly	*0%*	*0%*
	Assembly lead time	**0.6**	**0.8**
DMC	**Total workload**	**5.0**	**5.0**
	Forecast driven assembly	-3.2	-2.1
	% of total assembly	*-65%*	*-42%*
	Order driven, parallel assembly	-0.5	-0.6
	% of total assembly	*-9%*	*-12%*
	Assembly lead time	**1.3**	**2.3**
LSM	**Total workload**	**5.0**	**5.0**
	Forecast driven assembly	-2.5	-1.3
	% of total assembly	*-51%*	*-25%*
	Order driven, parallel assembly	-1.2	-1.4
	% of total assembly	*-23%*	*-28%*
	Assembly lead time	**1.3**	**2.3**
Material station	**Total workload**	**4.0**	**4.0**
	Forecast driven assembly	-2.2	-1.2
	% of total assembly	*-56%*	*-30%*
	Order driven, parallel assembly	0.0	0.0
	% of total assembly	*0%*	*0%*
	Assembly lead time	**1.8**	**2.8**

By combining tables 13 and 14, we can compose a table bridging the lead time diffence between non-modular and modular system in different scenarios. This table is presented as table 15.

Table 15: Lead time bridge from non-modular to modular system by impact factor

	Lead time impact breakdown	Base scenario		Risk scenario	
		Weeks	%	Weeks	%
Aisle	**Non-modular lead time**	**8.0**	100%	**8.0**	100%
	Impact to design	-0.8	-10%	-0.8	-10%
	Impact to purchasing	-3.0	-38%	-1.0	-13%
	Impact through forecast driven assembly	-0.4	-6%	-0.2	-3%
	Modular lead time	**3.8**	47%	**6.0**	75%
DMC	**Non-modular lead time**	**17.0**	100%	**17.0**	100%
	Impact to design	-4.8	-28%	-4.8	-28%
	Impact to purchasing	-2.0	-12%	0.0	0%
	Impact through forecast driven assembly	-3.2	-19%	-2.1	-12%
	Impact through parallel assembly	-0.5	-3%	-0.6	-4%
	Modular lead time	**6.5**	38%	**9.5**	56%
Electric	**Non-modular lead time**	**10.0**	100%	**10.0**	100%
	Impact to design	-4.0	-40%	-4.0	-40%
	Impact to purchasing	-1.0	-10%	1.0	10%
	Modular lead time	**5.0**	50%	**7.0**	70%
LSM (Critical path)	**Non-modular lead time**	**16.4**	100%	**16.4**	100%
	Impact to design	-2.0	-12%	-2.0	-12%
	Impact to purchasing	-3.4	-21%	-1.4	-9%
	Impact through forecast driven assembly	-2.5	-15%	-1.3	-8%
	Impact through parallel assembly	-1.2	-7%	-1.4	-9%
	Modular lead time	**7.3**	45%	**10.3**	63%
Material station	**Non-modular lead time**	**11.2**	100%	**11.2**	100%
	Impact to design	-2.0	-18%	-2.0	-18%
	Impact to purchasing	-9.2	-82%	-9.2	-82%
	Oursourced assembly to inhouse	1.8	16%	2.8	25%
	Modular lead time	**1.8**	16%	**2.8**	25%
System total	**Non-modular lead time**	**20.0**	100%	**20.0**	100%
	Impact to design	-2.0	-10%	-2.0	-10%
	Impact to purchasing	-3.4	-17%	-1.4	-7%
	Impact through forecast driven assembly	-2.5	-13%	-1.3	-6%
	Impact through parallel assembly	-1.2	-6%	-1.4	-7%
	Disconnecting assembly dependencies	-0.6	-3%	-0.6	-3%
	Modular lead time	**10.3**	52%	**13.3**	67%

In base scenario Aisle lead time was reduced by 4,2 weeks, -53 %, and in risk scenario 2 weeks, -25 %. The most significant lead time reduction for Aisle comes from reduction of purchasing lead time. Aisle purchasing time in non-modular scenario is 6 weeks, which reduced to 3 weeks, -38% of total Aisle lead time, in base scenario and to 5 weeks, -13 %

of total Aisle lead time, in risk scenario due to assumption “Short purchasing lead time for parametric components”.

Double mast crane, DMC, is in the critical path of the delivery process in the non-modular system, with lead time of 17 weeks. DMC lead time was reduced to 6,5 weeks, -62 %, in base scenario and to 9,5 weeks, -44 %, in risk scenario. Biggest impact to lead time for DMC was impact to design, as design time was reduced from 5 weeks to one day, -28 % of total DMC lead time, in both base and risk scenarios. This significant reduction in design lead time is born from assumption “Short design time”, which states that parametric modules are designed in one day, as designer needs to only adjust predetermined parameters for module, and no actual design work is needed.

Analyzing project phase Electric is more unambiguous task, as most of the contents in the non-modular Electric phase is reallocated and integrated to other system parts, like the double mast crane. What is left of the Electric phase is the Operator safety system component, which includes delivery specific modules. In total, Electric lead time was reduced from 10 weeks to 5 weeks, -50 %, in base scenario, and to 7 weeks, -30 %, in risk scenario. The biggest impact was the design time of Electric project phase, which was reduced from 5 weeks to 1 week, -40% of total Electric lead time, in both scenarios. The assumption regarding delivery specific design states that the design work needed for delivery specific modules is minimized by clever design solutions in the product development phase and delivery specific design is confined to chosen modules, and thus enables design lead time of one week for delivery specific modules. The difference between scenarios in Electric phase is born from difference in purchasing lead time, as purchasing lead time for Electric was reduced from 5 weeks to 4 weeks in base scenario but was increased from 5 weeks to 6 weeks in risk scenario.

Loading station moving, LSM, resides in the critical path of the delivery process in modular system. Lead time was reduced from non-modular system’s 16,4 weeks to 7,3 weeks, -55 %, in base scenario and to 10,3 weeks, -37 %, in risk scenario. LSM critical path goes through pallet station’s delivery specific module group in the modular system.

The biggest factor for lead time reduction for LSM is assembly, which was reduced from 5 weeks to 1,3 weeks, -22 %, in base scenario and from 5 weeks to 2,3 weeks, -17 %, in risk scenario. In the base scenario, 2,5 weeks, -15 % of total LSM assembly lead time, was saved by forecast driven assembly and 1,2 weeks, -7 % of total LSM assembly lead time, was saved by parallel assembly. In the risk scenario, 1,3 weeks, -8 % of total LSM assembly lead time, was saved by forecast driven assembly and 1,4 weeks, -9 % of total LSM assembly lead time, was saved by parallel assembly.

For LSM, the impact to purchasing was the second biggest factor for lead time reduction. Purchasing lead time was reduced from 7,4 weeks to 4 weeks, -21 % of total lead time of LSM, in base scenario and to 6 weeks, -9 % of total lead time of LSM, in risk scenario.

Impact to design was the smallest factor, reducing the design lead time of LSM from 3 weeks to 2 weeks, -12 % of total lead time of LSM, in both scenarios.

Material station lead time simulation for modular system is somewhat questionable, as material station as specified in this study changes from outsourced turnkey solution to completely renewed device with corresponding functionality, that is manufactured in-house. In this situation, Material station lead time was reduced from 11,2 weeks to 1,8 weeks, -84 %, in base scenario, and to 2,8 weeks, -75 %, in risk scenario. Most of the impact comes from purchasing, as its impact is -9,2 weeks, -82% of total Material station lead time, in both scenarios. This is slightly balanced by the assembly work that now needs to be done inhouse, which is only order driven task during delivery process of Material station, as interchangeable modules do not need design or purchasing during delivery process according to assumptions.

Looking at the total system, the critical path is predesign – LSM delivery specific processes – LSM final assembly – LSM test. This is the same critical path as LSM process has, except in the total system predesign is included. Because of this, the lead time impact is practically identical to that of LSM process, but in the total system delivery, 0,6 weeks, -3% of total system lead time, is saved from disconnecting the dependency of LSM and DMC from completion of Electric, as in the non-modular syste, DMC phase had to wait for Electric phase to finish before starting assembly of DMC. In total, system lead time was reduced from 20 weeks to 10,3 weeks, -42 %, in base scenario and to 13,3 weeks, -33 %, in risk scenario.

6. CONCLUSION

6.1 Discussion of findings

In this study, case company's current project delivery process was analyzed and normal lead time, from the beginning of the design phase to the point that all the assembly and testing at factory is completed and project is ready to be shipped, was estimated. After this, a simulation model for impact of modular product structure to lead time was created by combining insights from current literature with case company's current delivery process and company's vision of upcoming modular product structure. Using this simulation model, the research objective of critical factors and their impact to delivery process lead time was fulfilled.

6.1.1 Lead time impact and sensitivity analysis

With the assumptions made in the simulation model, project delivery process lead time was reduced from 20 weeks to 10,3 weeks, translating to 48 % lead time reduction. Impact to design lead time was -2 weeks, to purchasing lead time -3,4 weeks and to assembly lead time -3,7 weeks. Concerning the assembly lead time, - 2,5 weeks difference comes from forecast driven assembly work that is no longer needed during project delivery, and -1,2 weeks reduction is achieved through possibility to schedule assembly work in parallel to each other, in contrast to working in series with single timeline in assembly phase. In addition to these changes, simulated lead time includes 3 weeks of predesign and 1 week of factory testing. No changes were made to them compared to current situation, because predesign and testing included too much uncertainty to make assumptions about.

The lead time reduction in this simulation is significant. Looking at the simulated lead time, we can see that predesign lead time is 3 weeks, design lead time 1 week, purchasing lead time 4 weeks and total assembly lead time 1,3 weeks and testing lead time 1 week. Assuming the simulated design and assembly lead times are achieved, purchasing, and predesign processes present themselves as potential candidates for more lead time reduction, having relatively long lead times compared to design and assembly.

For sensitivity analysis, running the simulation with suboptimal assumptions about implementation success of modularity, we see that delivery process lead time is 13,3 weeks compared to 10,3 weeks in normal scenario. Here the assumption that delivery specific purchases takes 6 weeks compared to 4 weeks in base scenario, increase the total lead time by 2 weeks. Lead time is also increased by one week compared to base scenario due to lower amount of forecast driven assembly and higher amount of workload on the final assembly phase of the delivery. We conclude that even in risk scenario, lead time impact of modularity is significant, reducing the total lead time from 20 weeks to 13,3 weeks, translating to 33 % total lead time reduction. To manage the risk of this scenario realizing, attention should be used to fulfill the assumption “Decoupling of long lead time components and customer need”. Also, aiming to maximize the assembly work that can be done before the final assembly and designing individual modules so that they can be prefabricated to stock, maximizing the forecast driven assembly work, will affect the realized lead time when modularity is implemented to delivery process.

6.1.2 Lead time impact factors and enablers

In this chapter, we drill down to lead time impact factors and the assumptions that enable their realization. Design lead time is impacted by three assumptions stating that

- Standard and interchangeable modules: Modules are always standard or chosen from already designed alternatives and no design is needed.
- Parametric modules: Design is needed only to derive the module to customer need by changing pre-defined parameters of the module. Design time for module type group is 1 day.
- Delivery specific modules: Design effort required for delivery specific design is minimized by creating clever design solutions when designing the modular system structure and impact of customer specific needs for design is confined to chosen modules. One-week design lead time is needed

Looking at the assumptions, we can clearly see that each one of the assumptions are dependent on the concept of order penetration point postponement in the engineering dimension. To be able to postpone the order penetration point in the engineering dimension certain amount of commonality needs to be reached without sacrificing too much customization possibilities. This in turn boils down to making clever design decisions during the modular product structure development phase.

The assumptions concerning purchasing process per module type were:

- Standard and interchangeable modules: Demand for modules is high enough to justify stocking of all the needed materials. This eliminates purchasing time during delivery project.
- Parametric modules: Structure of the module is designed so that the components which are affected by the pre-defined parameters reliant on customer needs, have purchasing lead time of three weeks.
- Parametric and delivery specific modules: Product structure is designed so that long lead time components are not affected by the parameters defined by customer need. Maximum purchasing lead time of four weeks is assumed.

Again, the mechanism how these assumptions reduce purchasing lead time is based in postponing order penetration point, but now in production dimension. What enables these assumptions and thus postponement are the concepts of commonality, component standardization, multiple points of differentiation and relative demand volatility. The state of these concepts for delivery process is determined already in the modular product structure development phase, and thus should be considered early in the development process to maximize the lead time impact of modularity.

The last set of assumptions concern the assembly phase and state that:

- Standard modules: Module assembly can be made to stock and module assembly lead time is eliminated during the delivery project
- Interchangeable modules: Volume of interchangeable modules don't justify assembling and stocking completed modules. Module structure is mostly standard, but part of it derives the module to one of the pre-determined alternatives. Module bases are made to stock and completed during delivery project.
- Parametric and delivery specific modules: Module structure is mostly standardized, but there is a part which's dimensions or quantity can change according to customer need. Subassemblies of module can be made to stock and after customer order, the part that derives the module according to customer need can be manufactured and module can then be assembled. This reduces the lead time of the module as parts of it can be made to stock.

Once again, the way these assumptions reduce lead time is by postponing the order penetration point in production dimension, allowing for part of the assembly work to be forecast driven. For the postponement to be possible regarding the assembly phase, we can identify concepts of relative demand volatility, commonality, multiple points of differentiation, process standardization, process resequencing and component standardization as the key elements. Not all of the assembly lead time reduction is caused by order penetration postponement, as part of the lead time reduction in the simulation was caused by possibility of parallel assembly of module groups, reduction of 1,2 weeks, and disconnecting assembly dependencies, reduction of 0,6 weeks. Both impacts can be contributed to process resequencing enabled by modularity.

To conclude the discussion of results and factors impacting the lead time reduction, it seems that most of the delivery process lead time reduction potential is determined during the modular product structure development phase. The clever design decisions that find the right balance between commonality and customization of the system enable process resequencing, process standardization, component standardization and multiple points of differentiation which in turn make it possible to postpone the order penetration point in engineering and production dimensions if relative demand volatility so allows.

6.2 Theoretical contribution

This study contributes to operations management research area of modularity, specifically in project business. Modularity has been researched a lot in business segments where product volumes are high, but research addressing impacts of modularity for low volume or project type business is scarce. This study aims to increase the knowledge of modularity in project business by offering a novel way to analyze the impact of modularity to project delivery process and by highlighting the key factors and their impact mechanisms to delivery process lead time.

In this study, a novel framework to estimate implications of modularity to factory lead time was developed. For a project business pondering the implications of pursuing modularity for its project offering, this study can shed light on the implication of modularity in project delivery process. The simulation framework created in this study can be adopted as a basis for building similar simulations. Going through the process descriptions and assumptions of the model and changing them to fit the case at hand steers the researcher to focus on factors identified in this study as critical for lead time of delivery process.

6.3 Limitations

There are obvious limitations to generalization of this study's results. Study was conducted in one case company as a simulation of a possible future state. The design science methodology used, fundamentally works as a problem solving methodology and theory generation wise, belongs to solution incubation phase, where finding a solution that works is more important than exhaustively explaining why it works (Holmström et al., 2009).

The assumptions and following simulation are a result of an iterative process where ideas were searched from current literature and combined with known facts about current delivery process and company vision of the modular product structure in countless thought experiments. This process was above everything else, exploratory, and it is certain that all the possible alternatives were not considered or even identified during the process. Regardless of this, study should offer preliminary insights to mechanisms that impact the delivery process lead time of modular structure in project business. Also, this study creates a starting point that can be developed further by possible future studies continuing to explore the possibilities of lead time reduction of modularity in project business.

6.4 Further research

Logical continuity for this study simulating the future, would be appending the time horizon to longitudal to be able to compare the lead time simulation results with the actual modular delivery process lead time. Also, an analysis of the actual state of the factors that were identified as critical in this study should be conducted to deepen the understanding of these factors and their impact to delivery process lead time.

Studying the predesign phase could lead to further significant reductions of delivery process lead time in case company. Predesign phase lasts currently approximately 3 weeks and consists of specifying the system level configuration that has been sold to the customer. According to head of Fastems design department, Teemu Jaakkola (2016), the long lead time of predesign is mostly spent waiting and verifying for initial information needed to finish the predesign. Specifying what initial information is needed in the predesign phase and continuing to ensure that this initial information is already gathered during the end of sales phase, could make swift execution of predesign phase possible.

Purchasing phase lead time offers also interesting topic for research. Simplistically thinking, if the product owner can achieve significant delivery process lead time reduction through modularization, wouldn't this also enable product owner's suppliers to reap the benefits of modularization and thus reduce the purchasing lead times for product owner? Analyzing the impact of modularization downstream to first and second tier suppliers' processes combined with some form of partnership to develop suppliers' processes could lead to valuable findings.

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